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# Dynamic safety risk analysis of offshore drilling

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ABSTRACT

The exploration and production of oil and gas involve the drilling of wells using either one or a combination of three drilling techniques based on drilling fluid density: conventional overbalanced drilling, managed pressure drilling and underbalanced drilling. The conventional overbalanced drilling involves drilling of wells with mud which exerts higher hydrostatic bottom-hole pressure than the formation pore pressure. Unlike the conventional overbalanced drilling, underbalanced drilling involves designing the hydrostatic pressure of the drilling fluid to be lower than the pore pressure of the formation being drilled. During circulation, the equivalent circulating density is used to determine the bottom-hole pressure conditions. Due to lower hydrostatic pressure, underbalanced drilling portends higher safety risk than its alternatives of conventional overbalanced drilling and managed pressure drilling. The safety risk includes frequent kicks from the well and subsequent blowout with potential threat to human, equipments and the environment.

Safety assessment and efficient control of well is critical to ensure a safe drilling operation. Traditionally, safety assessment is done using static failure probabilities of drilling components which failed to represent a specific case. However, in this present study, a dynamic safety assessment approach for is presented. This approach is based on Bow-tie analysis and real time barriers failure probability assessment of offshore drilling operations involving subsurface Blowout Preventer. The Bow-tie model is used to represent the potential accident scenarios, their causes and the associated consequences. Real time predictive models for the failure probabilities of key barriers are developed and used in conducting dynamic risk assessment of the drilling operations. Using real time observed data, potential accident probabilities and associated risks are updated and used for safety assessment. This methodology can be integrated into a real time risk monitoring device for field application during drilling operations.



## 1. Introduction

The exploration and production of oil and gas involve the drilling of wells. Wells are drilled using either one or a combination of three drilling techniques based on drilling fluid density: conventional overbalanced drilling (COBD), managed pressure drilling (MPD), and underbalanced drilling (UBD) (Rehm, 2012). In COBD, the hydrostatic pressure of the drilling fluid (mud) column in the well is higher than the pore pressure of the formation. It involves the use of water based mud, oil based mud or synthetic drilling fluid which contains weighting materials to keep the bottom-hole pressure (BHP) above the formation pore pressure. This technique is relatively economical as it requires the least expertise and easiest well control as heavy mud is used; however, it is susceptible to lost circulation, reduced rate of penetration (ROP) and formation damage which affects reservoir productivity (Bennion, Thomas, Bietz, & Bennion, 1998).

On the other hand, in UBD, the effective circulating bottom-hole pressure of the drilling fluid is intentionally designed to be lower than the pressure of the formation being drilled. This technique leads to a reduction in the possibility of lost circulation and formation damage; an increase in reservoir productivity (to as much as 60% more than COBD (Gough & Graham, 2008)), ROP, bit life; an elimination of the need for costly mud systems and disposal of exotic mud with the use of water and light fluids; a minimization of differential pipe sticking, extensive and expensive completion and stimulation operations; and enables flow testing while drilling. However, it is susceptible to wellbore instability; suffers from an inability to use conventional measurement while drilling (MWD) technology; increases the cost of drilling due to the use of more equipment than conventional overbalanced drilling; requires highly skilled personnel as well control is complicated; and a carefully developed well plan is required (Bennion, Lunan, &

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Saponja, 1998; Leading Edge Advantage, 2002). This drilling method is often characterized as high risk drilling.

MPD, a derivative of UBD, has been defined by the International Association of Drilling Contractors (IADC) (Minerals Management Service, 2008) as "an adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular pressure profile accordingly." It reduces lost circulation and formation damage, while increasing ROP. However, more equipment, higher expertise for well control and higher risks are involved than conventional overbalanced drilling (Haghshenas, Paknejad, Reihm, & Schubert, 2008).

The choice of drilling technique is determined by the formation pressure (abnormally, normally or sub-normally pressured), nature of reservoir fluid (gas, condensate or black oil), type of well (exploratory, development, re-entry), formation geology (fractured or unconsolidated reservoirs), accessibility (onshore or offshore), economics, equipment availability, government policies or regulations and associated risks. Since most formation and reservoir properties are characterized with high uncertainty – exploratory and development drilling operations are associated with various forms of risks which have led to major rig accidents in the past: Ocean Ranger rig accident, in February, 1982, Deepwater Horizon drilling rig explosion, in April, 2010, Vermillion Oil Rig 380 explosion, in September, 2010 and Chevron Nigeria limited oil rig explosion, in January, 2012 (Arnold & Itkin LLP, 2014).

As drilling is a hazardous operation, safety is one of the major concerns. Safety is often measured in terms of risk (Khan, 2001). Risk is defined as a measure of accident likelihood and the magnitude of loss (fatality, environmental damage and/or economic loss). Risk analysis involves the estimation of accident consequences and frequencies using engineering and mathematical techniques (Crowl & Louvar, 2002). Various techniques have been developed for quantitative risk analysis; the foremost among the conventional methods are fault tree and event tree analyses. The results of these analyses are used in risk assessment to evaluate the safety provided for preventing or mitigating the consequences of accidents. Conventional risk assessment techniques are known to be static; failing to capture the variation of risks as operation or changes in the operation take place (Khakzad, Khan, & Amyotte, 2012). Besides, conventional risk assessment techniques make use of generic failure data; making them to be non-case-specific and also, introduces uncertainty into the results. These limitations have led to the development of dynamic risk assessment method. Dynamic risk assessment method is meant to reassess risk in terms of updating initial failure probabilities of events (causes) and safety barriers as new information are made available during a specific operation. Two ways are currently used in revising prior failure probabilities: (i) Bayesian approaches through which new data in form of likelihood functions are used to update prior failure rates using Bayes' theorem (Meel & Seider, 2006; Kalantarnia, Khan, & Hawboldt, 2009; Kalantarnia, Khan, & Hawboldt, 2010; Khakzad, Khan, & Amyotte, 2012). (ii) Non-Bayesian updating approaches in which new data are supplied by real time monitoring of parameters, inspection of process equipments and use of physical reliability models (Ferdous, Khan, Sadiq, Amyotte, & Veitch, 2013; Khakzad, Khan, & Amyotte, 2012; Shalev & Tiran, 2007).

Underbalanced drilling is undertaken to maximize hydrocarbon recovery while minimizing drilling problems. However, it is associated with safety concerns as a result of the BHP being always less than the formation pore pressure which increases the possibility of kicks and blowout, thus, endangers personnel, facilities as well as the environment. There are a few studies on the risk analysis of overbalanced drilling (Anderson, 1998; Bercha, 1978; Khakzad, Khan, & Amyotte, 2013; Khakzad, Khakzad, & Khan, submitted for publication; Khakzad, Khan, & Palterinieri, 2014; Rathnayaka, Khan, & Amyotte, 2013; Skogdalen & Vinnem, 2012) and modeling of BOP systems (Fowler & Roche, 1994; Holland, 1991, 2001). The study of MPD and UBD is limited to Safety and Operability (SAFOP) analysis (Engevik, 2007).

The present study is aimed at conducting a dynamic quantitative risk assessment of drilling operations using advanced approach that can use real time data from the operation. The main objectives of this study are: (i) to develop a detailed quantitative risk analysis model that helps to assess and update the risk during drilling operation and (ii) to identify most vulnerable causes that have propensity to cause accident (blowout). Knowing these will help to design blowout prevention and mitigation measures. The study is focused on offshore application of three drilling techniques with subsurface blowout preventer (BOP). A brief description of drilling techniques and a description of dynamic risk methodology are presented in subsequent sections.

## 2. Drilling techniques

### 2.1. Conventional Overbalanced Drilling (COBD)

COBD involves drilling of a well with a drilling mud whose hydrostatic pressure is deliberately kept higher than the BHP. It is the basis of rotary drilling, thus, the commonest technique in the oil and gas industry. It is practiced because of its ease of well control, requiring the least planning, least expensive as the basic equipments of rotary drilling are used and the least number of crew members of all drilling techniques. The mud composition stabilizes the wellbore and is also compatible with all types of MWD tools; however, it has the least rate of penetration due to heavy mud used and could lead to lost circulation, stuck piping and formation damage (Adams, 1985; Bourgoyne, Millheim, Chenevert, & Young, 1986).

### 2.2. Underbalanced Drilling (UBD)

UBD includes drilling techniques employing appropriate equipment and controls to drill a well at a wellbore pressure less than the pore pressure in any part of the exposed formations in order to bring formation fluid to the surface (IADC) (Rehm, 2012). It is classified into two categories based on the type of drilling fluid: single phase fluids and two-phase (gaseous and compressible) fluids. The single phase fluid drilling comprises all underbalanced drilling techniques that do not use compressible gases as drilling fluid. It includes water, oil and additives such as glass beads. Two-phase fluid drilling, otherwise known as compressible fluid drilling, utilizes compressible fluids such as air, mist, foam and aerated mud (Leading Edge Advantage, 2002). Other forms of UBD are coiled tubing drilling, liner drilling and casing while drilling. In UBD operation, COBD equipments are used in addition to specialized facilities which include: rotating control device (RCD), snubbing unit, drill-string non-return valves, compressors for gas generation (if applicable) and dedicated choke manifold (Bennion, Lunan, & Saponja, 1998; Bennion, Thomas, Bietz, & Bennion, 1998; Gough & Graham, 2008; Hannegan & Wanzer, 2003; Leading Edge Advantage, 2002).

### 2.3. Managed Pressure Drilling (MPD)

MPD like UBD is a closed-loop fluid system requiring some of the UBD's specialized equipment: RCD, drill-string non-return valve and a dedicated choke manifold. It uses a single-phase drilling fluid to produce minimal friction losses. It is also described as near-balanced drilling as the mud hydrostatic pressure is kept close to the formation pore pressure, hence, it is called a constant bottom-hole pressure drilling technique. MPD unlike UBD avoids kicks during drilling. It has the ability to reduce non-productive time, making it a candidate for offshore drilling consideration (Haghshenas, Paknejad, Reihm, & Schubert, 2008; Cohen, Stave, Schubert, & Elieff, 2008; Fredericks, 2008; Vogel & Brugmann, 2008; Rehm, 2012; Smith & Patel, 2012).

### 2.4. Well control considerations

Well control operations deal with the procedures to be undertaken when formation fluids start flowing into the wellbore and displacing the drilling fluid. This flow of formation fluids into the wellbore is called kick while the uncontrolled flow to the surface is known as blowout. In COBD, the primary well control is the drilling mud. During well control operations, early detection of kicks is sought. The well is shut in with the blowout preventer (BOP) – first with the annular preventer, followed by the pipe ram and lastly, with the shear ram in a very dangerous situation. Depending on the method (Driller's method or Engineer's method), kick fluid is circulated to the surface using Kill mud (heavy mud) to bring the well under control via the kill/choke lines (Bourgoyne , Millheim, Chenevert, & Young, 1986). However, in UBD, since less BHP compared to formation pore pressure is desired; flow of formation fluid into the well is induced. Instead of shutting in the well, the kick fluid is circulated in a controlled manner with the combination of the rotating control device, diverter line and the choke system to the surface. Control over too much or too little flow of formation fluid into the well is done by changing the BHP through increasing or decreasing the choke pressure, changing the drilling fluid density for single phase flow, changing the liquid to gas ratio with two-phase fluid and changing the pump rate. The drilled cuttings together with the formation fluid mix with the drilling fluid and flow via the annulus en route to the surface. The mixture is separated at the surface into its constituents, i.e. drilling fluid, drilled cuttings, formation fluids of oil, water and natural gas. The oil is stored temporarily in an atmospheric storage tank while the natural gas is stored, flared or re-injected into the annulus with the air (or nitrogen) to lighten the column of fluid (Gough & Graham, 2008; Hannegan & Wanzer, 2003).

## 3. Dynamic risk assessment

Conventional risk assessment methods such as fault tree and event tree analyses have commonly been used in accident modeling and risk quantification. These methods are simple and provide quick results and inferences. The combination of fault and event trees forms a Bow-tie (BT) risk model. A BT model has the top event of the fault tree as the initiating event of the event tree. The BT diagram presents a logical relationship between the causes (expressed as basic events) to the consequences through safety barriers. Markowski and Agata (2011) used BT in layer of protection analysis to model a complete accident scenario in a hexane distillation unit. Similarly, forms of BT have been applied in medical safety risk analysis and hazard and effects management process of vehicle operations (Wierenga et al., 2009; Eslinger et al., 2004). Due to the limitations of conventional risk assessment techniques stated in Section 1, recent studies have led to the development of advanced dynamic risk assessment methods. These dynamic risk assessment methods are meant to update the initial failure probabilities events (causes) and safety barriers as new information are available. A few studies are reported using dynamic risk approach based on BT approach (Khakzad, Khan, & Amyotte, 2012; Khakzad, Khan, & Amyotte, 2013; Rathnayaka, Khan, & Amyotte, 2013). In this present work, a dynamic bow-tie risk model for offshore drilling operations is developed and analyzed for safety critical operation decision-making.

### 3.1. Bow-tie risk model of drilling operations

A bow-tie risk model for offshore application of COBD, UBD and MPD is developed (Fig. 1). In the diagram, BE, IE and TE represent the basic event (component or action), intermediate event and top event respectively of the fault trees of Figs. 2 and 3. TE, SB and C are the initiating event, safety barrier and consequence of the event tree in Fig. 4. Only the well section is modeled in this study, surface facilities are not included. The potential causes of kick are based on the work of Kato and Adams (1991). The well control mechanism prevents the occurrence of a kick as in COBD and MPD or mitigates its effects as in UBD. The well control mechanism also prevents a kick from resulting to a blowout; hence, is placed side by side with kick in the fault tree in Fig. 2. The collapse of the rig, natural and artificial disasters which can lead to loss of well control are external to the BOP system. The BOP system prevents or mitigates the effects of the collapse of a rig, natural and artificial disasters and the eventual loss of primary well control in the circulation system. The BOP system comprises rotating control device (RCD), the snubbing unit, the diverter system and the conventional subsea BOP stack. The success of UBD and MPD operation relies on the well control mechanism of the RCD with particular emphasis on the seal in conjunction with a dedicated choke manifold (Hannegan & Wanzer, 2003). The snubbing unit serves as backup for the RCD. In COBD operation, the diverter system is provided for shallow gas handling to prevent premature formation fracturing. Ultimately, well control is assured with the conventional subsea BOP stack.

The BOP stack comprises the lower marine riser package (LMRP), the lower annular preventer and the ram preventers – upper pipe ram or variable bore ram, middle pipe ram, lower pipe ram, casing shear ram and blind shear ram. These dictate the general structures of the fault trees in Figs. 2 and 3. In the formulation of the model, efforts were focused on safety critical components and actions. In other words, only the fault condition or failure mode of the components which is critical to the failure of the system and resulting to undesired condition (hydrocarbon blowout) is studied. Components such as the redundant fail-safe valves connecting the choke and kill lines to the BOP and the choke and kill lines themselves are not duplicated in the fault tree; rather, their aggregated failure probabilities are used. The characteristics of the components and their corresponding probabilities are presented in Table 1 (Bercha, 1978; Khakzad, Khan, & Amyotte, 2013; OREDA, 2002).

The event tree (Fig. 4) part of the Bow-tie model comprises of three safety barriers, namely: Ignition Prevention Barrier (IPB), Escalation Prevention Barrier (EPB) and Damage Control & Emergency Management Barrier (DC&EMB). The IPB includes means for preventing ignition by sparks, friction, impact or hot surface which include hydrocarbon detection and alarm system, hot surface shields, sparks and friction inhibitors. EPB comprises fire and gas detection, suppression and alarm system, automatic sprinkler system and onsite fire extinguishers. DC&EMB involves external intervention such as fire fighting service to reduce and control the damage resulting from the escalating fire and explosions. Also, it includes training of crew members on emergency response procedures and provision of facilities for safe escape and evacuation from the site (Rathnayaka, Khan, & Amyotte, 2011).

The success of IPB prevents blowout from resulting to a primary vapor cloud explosion or pool fire. However, a minor to significant vapor cloud/oil spill to the marine environment is experienced depending on the duration. Vapor cloud explosion/pool fire occurs if the IPB fails, leading to a significant pollution to the environment with minor injuries to personnel. Secondary explosions and fire occur as a result of the failure of IPB and EPB. A significant damage to the rig and the environment is recorded with life threatening

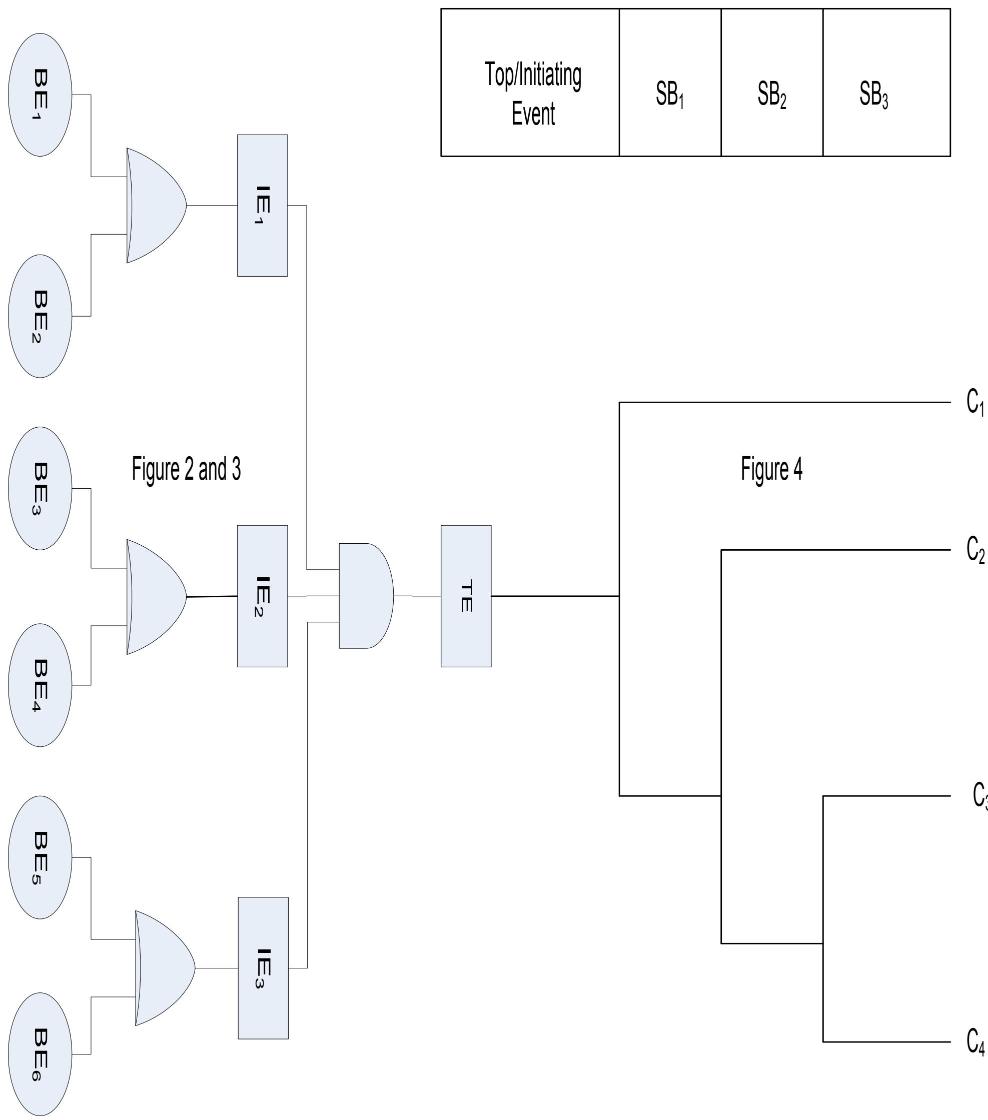


**Fig. 1.** Bow-tie risk model for drilling operations.

injuries to a few deaths. Finally, event leads to a catastrophe characterized with a severe damage to the well, rig, long term environmental damage as a result of prolonged oil spill and multiple fatalities. Though consequence severity levels and their corresponding loss values are case specific and vary among companies; a summary of the consequence severities and their loss values used in this study is presented in Table 2.

### 3.2. Predictive probabilistic model

Drilling equipments are often rated by their working pressures. The components such as the rotating control device (RCD), choke manifold, BOP, valves, choke and kill lines, snubbing unit and diverter system are designated with their working pressure ratings which signify the pressures beyond which they are bound to fail. The real time predictive failure probabilities of these components are modeled using physical reliability model of constant strength and random stress of exponential distributions (Ebeling, 1997). The strength, $k$, represents the working pressure rating of the component while the stress, $\sigma$, is the formation pressure present during drilling. The component fails when the load (stress) is greater than its strength. Mathematically, the failure probability of the component (PC) is given as:

$$\Pr(\text{PC failure}) = \Pr(\sigma > k) = \int_k^\infty f_\sigma(\sigma)\mathrm{d}\sigma \quad (1)$$

Thus, for exponential stress distribution:

$$\Pr(\text{PC failure}) = \int_k^\infty \lambda \exp(-\lambda\sigma)\mathrm{d}\sigma = \exp(-\lambda k) \quad (2)$$

The mean of exponential distribution is given as:

$$E(\sigma) = 1/\lambda \quad (3)$$

$$\Pr(\text{PC failure}) = \exp(-k/E(\sigma)) \quad (4)$$

where $E(\sigma)$ is the expected value of the measured formation pressure. The formation pressure is measured using mud pulse telemetry tool in COBD and MPD and electromagnetic telemetry tool in

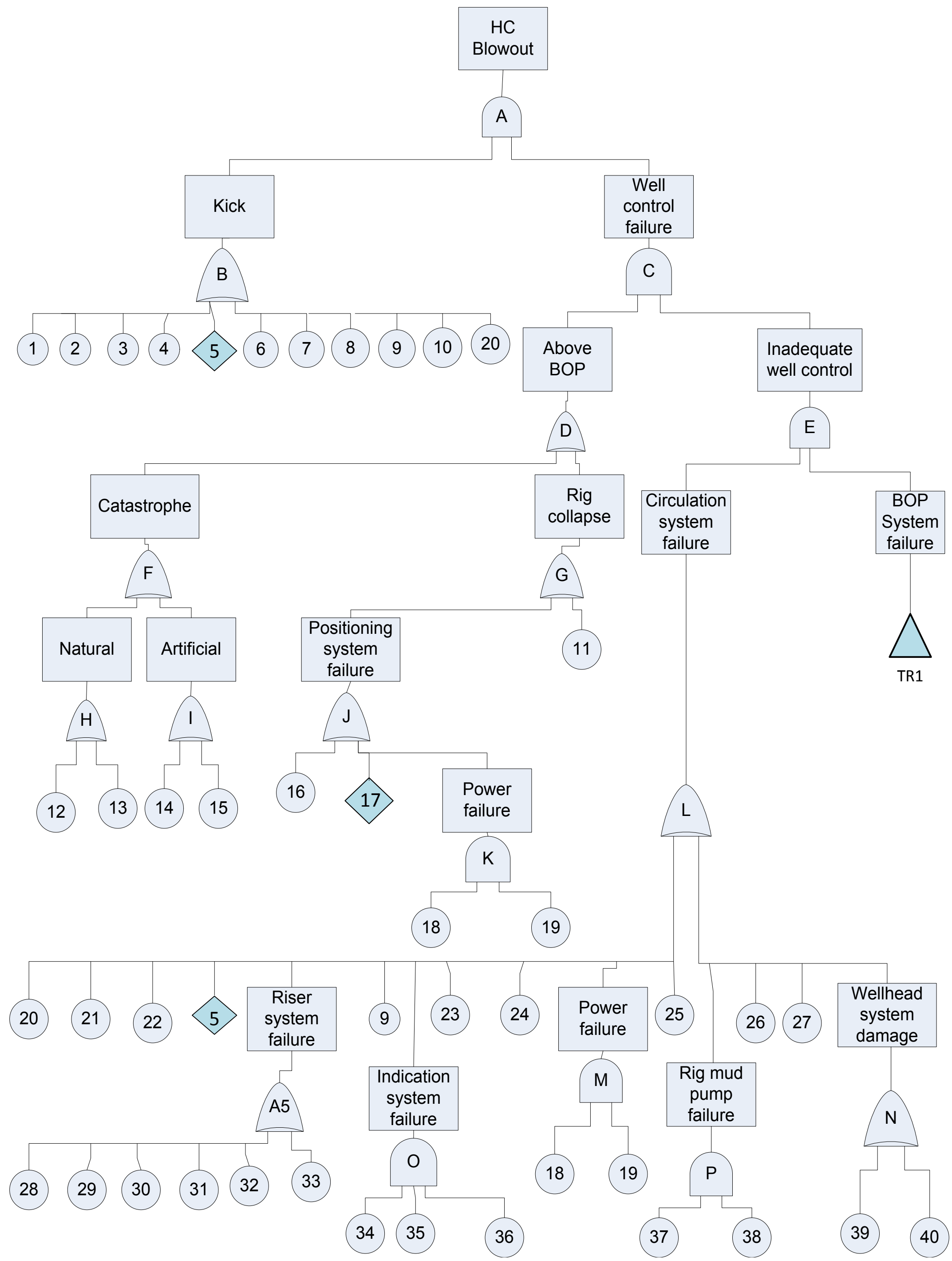


**Fig. 2.** Fault tree model for drilling operations.

UBD or other logging while drilling (LWD)/measurement while drilling (MWD) tools. The components highlighted above are at a true vertical height *h (ft)* from the bottom hole, thus, equation (4) becomes:

$$\Pr(\text{PC failure}) = \exp(-k/(E(\sigma) - 0.052^*ECD^*h)) \tag{5}$$

where *ECD* (*ppg*) is the equivalent circulating density of the mud comprising the mud hydrostatic pressure and the frictional pressure loss in the annulus. *k and* $E(\sigma)$ are both in *psi*. $E(\sigma)$ can also be expressed as a function of *h* as

$$E(\sigma) = 0.433h \tag{6}$$

for fresh water formation fluid or as

$$E(\sigma) = 0.465h \tag{7}$$

for salt water formation fluid (Adams, 1985; Bourgoyne, Millheim, Chenevert, & Young, 1986).

The failure probabilities of the safety barriers *(SB)* of the event tree are updated by Bayes's theorem (Equation (8)) with the accident precursor data (APD) gathered as the drilling operation progresses, leading to posterior failure probabilities (Bedford & Cooke, 2001)

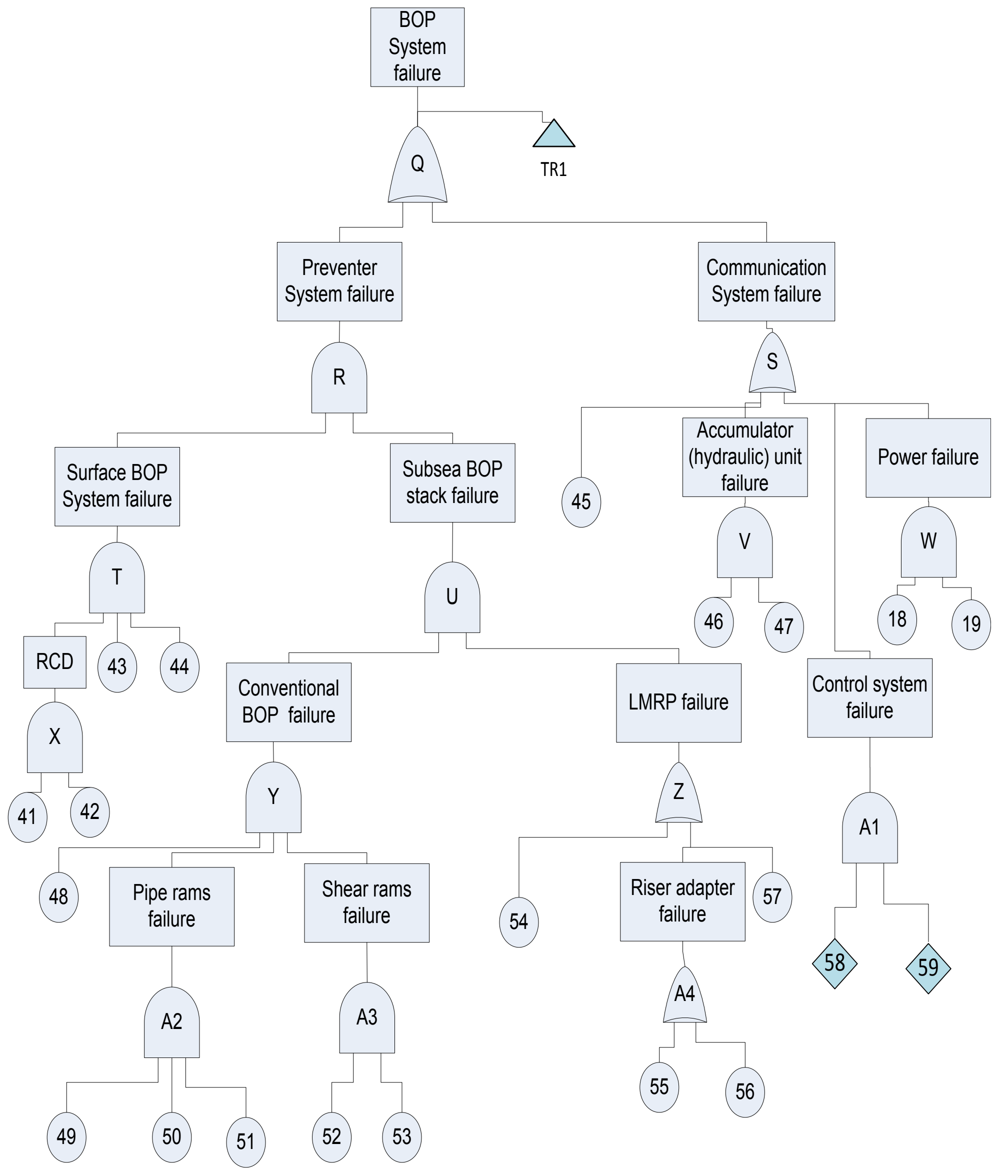


**Fig. 3.** Fault tree model for drilling operations (continued).

$$p(\mathrm{SB}_i/\mathrm{APD}) = (p(\mathrm{APD}/\mathrm{SB}_i)p(\mathrm{SB}_i))\Big/\left(\sum p(\mathrm{APD}/\mathrm{SB}_i)p(\mathrm{SB}_i)\right) \tag{8}$$

where $p(SB_i)$ is the prior failure probability of $SB_i$, $p(APD/SB_i)$ is the likelihood function derived from the accident precursor data and $\sum p(\mathrm{APD}/\mathrm{SB}_i)p(\mathrm{SB}_i)$, is the normalizing factor. Thus, the occurrence frequencies of the various consequences of the event tree are updated through Bayes theorem.

### 3.3. Bow-tie model analysis

The Bow-tie model analysis follows the algorithm shown in Fig. 5. The components applicable to the drilling technique are identified. The prior failure probabilities of these components and that of the safety barriers are determined. These are used to compute the probabilities of blowout occurring and subsequently, the prior frequencies of the consequences. As drilling progresses, failure probabilities of components are updated using Equation (5). In addition, accident precursor data are collected and used to update the probabilities of the safety barriers. Both are used to obtain the posterior (updated) frequencies of the consequences. These are compared with the threshold frequency of end event(s) set by established literature/industry values/based on experience. Drilling operation is continued if the posterior frequencies are less than the threshold frequency; otherwise, drilling is halted, a review of component capacities or pressure ratings and necessary modifications are made before drilling operation progresses. In this way, safety is ensured, unnecessary downtime and accidents are prevented.

A comparison is made between COBD and UBD considering the following conditions:

- permeability of the formation is sufficiently high
- the reservoir is sufficiently pressured as to support hydrocarbon influx into the well (kick) and the subsequent blowout if all the relevant barriers fail
- for COBD, rotating control device (RCD), dedicated choke manifold and snubbing unit are not used.

With the probabilities presented in Table 1, the occurrence probability of a blowout for COBD is estimated as 7.97E-04. For UBD operation, the probability of a blowout is estimated as 5.70E-03 as a

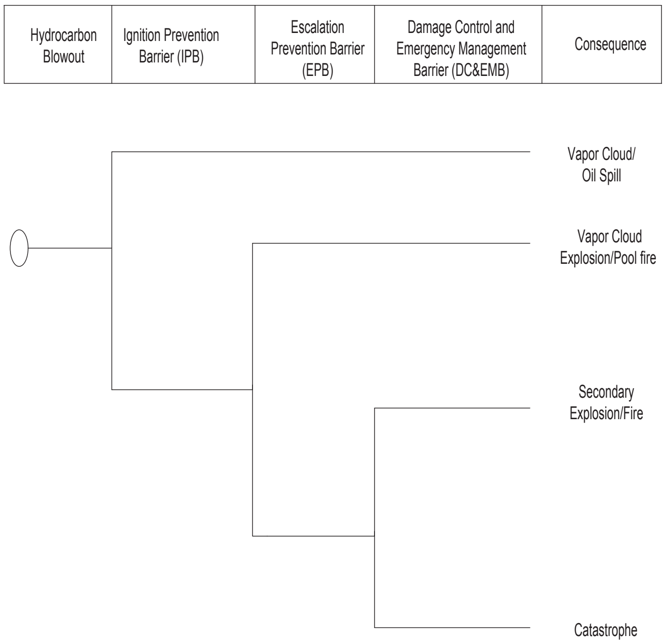


**Fig. 4.** Event tree model for consequence analysis.

result of insufficient ECD. It is noticed that the chance of having a blowout is increased by a factor of 7 in UBD operation as opposed to COBD.

Furthermore, in the course of drilling, the primary well control (drilling mud) is relied on for COBD while the functions of RCD and the choke manifold together with the drilling fluid of insufficient mud weight are employed to provide primary well control for UBD operation. The well is then not shut in with the BOP except when well control is in danger; thus, the functions of the BOP for both techniques and the snubbing unit are relaxed. Under this condition, occurrence probability of a blowout for COBD is estimated as 1.50E-02 while for UBD, the occurrence probability is estimated as 5.80E-03. It is observed that the occurrence probability of a blowout in COBD almost tripled that of UBD. This shows the importance of RCD in assuring the safe operation of UBD. RCD has been identified critical to ensure the success of UBD (Hannegan & Wanzer, 2003). It is worth mentioning that seals are critical elements of RCD, thus, must be best designed and maintained.

The failure probability of RCD seals with a redundant pair arrangement in the above analysis is 6.70E-03. Assuming a salt water formation and using Equations (5) and (7), a well depth of 4000 ft should not be exceeded for gasified drilling fluid of density 4 ppg and a well depth of 20,000 ft for water drilling mud could be achieved while keeping the failure probability of RCD below 6.70E-03 as shown in Table 3 and Fig. 6. This behavior of water drilling mud is supported by the observations in MPD where the density of the drilling fluid is kept as close as possible to the formation pressure. However, with the modern formation pressure measurement while drilling tools, precise stress determination is ensured. The prior failure probabilities of the safety barriers are listed in Table 4. A set of accident precursor data from a UBD operation is presented in Table 5. These are the cumulative number of abnormal events that were observed over the period of 24 h towards the major accident (catastrophe). For example, the cumulative number of vapor cloud/oil spill end events at the 22nd h is 13 as shown in Table 5. The accident precursor data are used to update the failure probabilities of the safety barriers – Ignition Prevention Barrier (IPB), Escalation Prevention Barrier (EPB) and Damage Control and Emergency Management Barrier (DC&EMB).

The prior occurrence frequencies of the consequences with a blowout probability estimated as 5.80E-03 are presented in Table 6. The updated failure probabilities of safety barriers are shown in Table 7 (bold and italic) using Equation (8). For illustration purposes, at the 22nd h, for IPB, the likelihood function is determined by the ratio of the number of failures (5 + 1) to the total number of abnormal events (functions and failures, 13 + 5 + 1) at that instant. That is,

**Table 1**
Basic events and their probabilities (Bercha, 1978; Khakzad, Khan, & Amyotte, 2013; OREDA, 2002).

| Basic event | Description | Probability |
|---|---|---|
| 1 | Abnormal pressured zone | 1.50E-01 |
| 2 | Swabbing | 5.40E-02 |
| 3 | Gas cut mud | 3.00E-05 |
| 4 | Inadequate hole fill up | 2.00E-03 |
| 5 | Bad cementing | 1.00E-03 |
| 6 | Gas pocket/shallow gas | 3.00E-05 |
| 7 | Stuck pipe | 1.00E-03 |
| 8 | Drillpipe failure | 5.00E-05 |
| 9 | Insufficient ECD | 5.00E-02 |
| 10 | Loss circulation | 2.70E-03 |
| 11 | Poor design | 5.00E-04 |
| 12 | Storm/Hurricane | 3.00E-05 |
| 13 | Ice | 3.00E-05 |
| 14 | War/Vandalism | 3.00E-05 |
| 15 | Collision of ships | 3.00E-05 |
| 16 | Operator error (positioning) | 2.00E-03 |
| 17 | Dynamic positioning failure | 5.00E-04 |
| 18 | Primary power failure | 5.00E-04 |
| 19 | Secondary power failure | 5.00E-04 |
| 20 | Casing failure | 6.40E-04 |
| 21 | Drill pipe failure | 5.00E-04 |
| 22 | Choke/kill lines failure | 3.60E-04 |
| 23 | ESD valve failure | 1.30E-04 |
| 24 | Failsafe valves failure | 2.20E-04 |
| 25 | Operator error (mud engineering) | 1.00E-03 |
| 26 | Choke manifold failure | 4.51E-03 |
| 27 | Drill pipe non-return valve failure | 1.30E-04 |
| 28 | Riser connector failure | 1.00E-04 |
| 29 | Riser stand failure | 1.00E-04 |
| 30 | Telescopic joint failure | 1.00E-04 |
| 31 | Wave motion compensator failure | 1.00E-04 |
| 32 | Tensioner failure | 1.00E-04 |
| 33 | Automatic fill up valve failure | 1.00E-05 |
| 34 | Pit level indicator failure | 2.00E-04 |
| 35 | Pump stroke failure | 2.00E-04 |
| 36 | Mud flow indicator failure | 2.00E-04 |
| 37 | Main pump failure | 4.30E-03 |
| 38 | Backup pump failure | 4.30E-03 |
| 39 | Wellhead housing damage | 1.00E-05 |
| 40 | Wellhead connector failure | 1.00E-05 |
| 41 | Primary RCD seal failure | 6.70E-03 |
| 42 | Backup RCD seal failure | 6.70E-03 |
| 43 | Diverter system failure | 3.60E-03 |
| 44 | Snubbing unit failure | 4.30E-03 |
| 45 | Operator error (BOP) | 2.00E-03 |
| 46 | Primary accumulators failure | 1.00E-05 |
| 47 | Backup accumulators failure | 1.00E-05 |
| 48 | Lower annular preventer failure | 2.60E-04 |
| 49 | Upper/Variable pipe ram failure | 2.50E-05 |
| 50 | Middle pipe ram failure | 2.50E-05 |
| 51 | Lower pipe ram failure | 2.50E-05 |
| 52 | Blind shear ram failure | 1.00E-05 |
| 53 | Casing shear ram failure | 1.00E-06 |
| 54 | Upper annular preventer failure | 2.60E-04 |
| 55 | Upper flexible joint failure | 1.00E-05 |
| 56 | Lower flexible joint failure | 1.00E-05 |
| 57 | LMRP connector failure | 1.00E-05 |
| 58 | Main control system failure | 2.52E-02 |
| 59 | Acoustic backup control system failure | 2.52E-02 |

**Table 2**
Consequence severity levels and loss values.

| Event | Severity level | Description | Loss value (M USD) |
|---|---|---|---|
| Vapor cloud/oil spill | 1 | Minor to significant vapor cloud/oil spill | 100 |
| Vapor cloud explosion (VCE)/pool fire | 2 | VCE/pool fire occurs due to ignition, significant pollution to the environment, minor injury to personnel | 200 |
| Secondary explosion/fire | 3 | Multiple explosions occur with prolonged fire, major damage to rig, environment, life threatening injuries to a few fatalities | 750 |
| Catastrophe | 4 | Continuous fire with severe damage to well, rig, environment, multiple fatalities | 5000 |

$p(\text{APD}/\text{SB}_{\text{IPB}}) = 6/19 = 0.3158.$

The posterior probability of IPB at the 22nd h is calculated as:

$$p(\text{SB}_{\text{IPB}}/\text{APD}) = p(\text{APD}/\text{SB}_{\text{IPB}})p(\text{SB}_{\text{IPB}}) \Big/ \sum (p(\text{APD}/\text{SB}_{\text{IPB}})p(\text{SB}_{\text{IPB}}))$$

$$p(\text{SB}_{\text{IPB}}/\text{APD}) = (0.3158)(2.72\text{E-}02)/((0.31583)(2.72\text{E-}02) + (.6842)(.9728)) = 1.27\text{E-}02.$$

The posterior failure probabilities of the safety barriers and the probability of blowout are used to determine occurrence frequencies or probabilities of end events by event tree analysis and presented in Table 8. The posterior occurrence frequency of vapor cloud/oil spill for a blowout probability of 5.80E-03 at the 22nd h is: 5.80E-03 * (1 − 1.27E-02) = 5.73E-03.

The risk value of vapor cloud/oil spill is then: 5.73E-03 * 100,000,000 = $573,000.

For other abnormal events that were not observed during the period of the investigation, the prior estimates of the failure probabilities of the corresponding safety barriers are used for event tree analysis. A closer look at the occurrence frequency profiles of the end events (Fig. 7) reveals a progressive increase in the occurrence frequency of VCE/pool fire (in consonance with a decreasing trend in the frequency of VC/oil spill event of lesser severity) after the 21st hour. This is due to a reduction in the effectiveness of or an increase in the failure probability of the IPB as discussed in Section 3.1. If the threshold frequency for VCE/pool fire event had been set to a value of 8.00E-05, the drilling operation would have been halted at the 22nd h and a review of the operation carried out. This would have prevented the catastrophic event that was likely at the 24th hour. This is corroborated by an increase in the frequencies of secondary explosion/fire and catastrophic events at the 22nd h (Fig. 8). A decrease in the frequency of the catastrophic event after

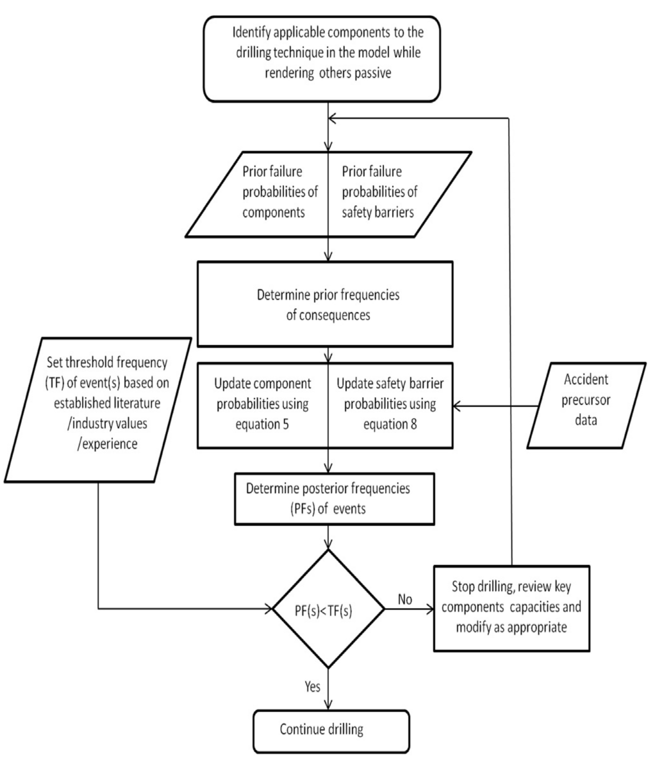


**Fig. 5.** Bow-tie analysis algorithm.

**Table 3**
Failure probabilities of the RCD with water and gasified fluid drilling mud.

| Depth, $h$(ft) | Stress, $E(\sigma)$, (psi) | Strength, $k$, (psi) | Failure probabilities | |
|---|---|---|---|---|
| | | | Water | Gasified fluid |
| 500 | 232.5 | 5000 | ≈0 | ≈0 |
| 1000 | 465 | 5000 | ≈0 | ≈0 |
| 1500 | 697.5 | 5000 | ≈0 | 2.33E-06 |
| 2000 | 930 | 5000 | ≈0 | 5.96E-05 |
| 2500 | 1162.5 | 5000 | ≈0 | 4.17E-04 |
| 3000 | 1395 | 5000 | ≈0 | 1.53E-03 |
| 3500 | 1627.5 | 5000 | ≈0 | 3.85E-03 |
| 4000 | 1860 | 5000 | ≈0 | 7.72E-03 |
| 4500 | 2092.5 | 5000 | ≈0 | 1.33E-02 |
| 5000 | 2325 | 5000 | ≈0 | 2.04E-02 |
| 5500 | 2557.5 | 5000 | ≈0 | 2.91E-02 |
| 6000 | 2790 | 5000 | ≈0 | 3.91E-02 |
| 6500 | 3022.5 | 5000 | ≈0 | 5.01E-02 |
| 7000 | 3255 | 5000 | ≈0 | 6.21E-02 |
| 7500 | 3487.5 | 5000 | ≈0 | 7.47E-02 |
| 8000 | 3720 | 5000 | ≈0 | 8.79E-02 |
| 8500 | 3952.5 | 5000 | ≈0 | 1.01E-01 |
| 9000 | 4185 | 5000 | 2.64E-08 | 1.15E-01 |
| 9500 | 4417.5 | 5000 | 6.62E-08 | 1.29E-01 |
| 10,000 | 4650 | 5000 | 1.51E-07 | 1.43E-01 |
| 10,500 | 4882.5 | 5000 | 3.20E-07 | 1.57E-01 |
| 11,000 | 5115 | 5000 | 6.31E-07 | 1.71E-01 |
| 11,500 | 5347.5 | 5000 | 1.17E-06 | 1.84E-01 |
| 12,000 | 5580 | 5000 | 2.07E-06 | 1.98E-01 |
| 12,500 | 5812.5 | 5000 | 3.50E-06 | 2.11E-01 |
| 13,000 | 6045 | 5000 | 5.67E-06 | 2.24E-01 |
| 13,500 | 6277.5 | 5000 | 8.88E-06 | 2.37E-01 |
| 14,000 | 6510 | 5000 | 1.34E-05 | 2.49E-01 |
| 14,500 | 6742.5 | 5000 | 1.98E-05 | 2.61E-01 |
| 15,000 | 6975 | 5000 | 2.84E-05 | 2.73E-01 |
| 15,500 | 7207.5 | 5000 | 3.98E-05 | 2.85E-01 |
| 16,000 | 7440 | 5000 | 5.46E-05 | 2.96E-01 |
| 16,500 | 7672.5 | 5000 | 7.36E-05 | 3.08E-01 |
| 17,000 | 7905 | 5000 | 9.73E-05 | 3.18E-01 |
| 17,500 | 8137.5 | 5000 | 1.27E-04 | 3.29E-01 |
| 18,000 | 8370 | 5000 | 1.63E-04 | 3.39E-01 |
| 18,500 | 8602.5 | 5000 | 2.06E-04 | 3.49E-01 |
| 19,000 | 8835 | 5000 | 2.57E-04 | 3.59E-01 |
| 19,500 | 9067.5 | 5000 | 3.18E-04 | 3.69E-01 |
| 20,000 | 9300 | 5000 | 3.89E-04 | 3.78E-01 |

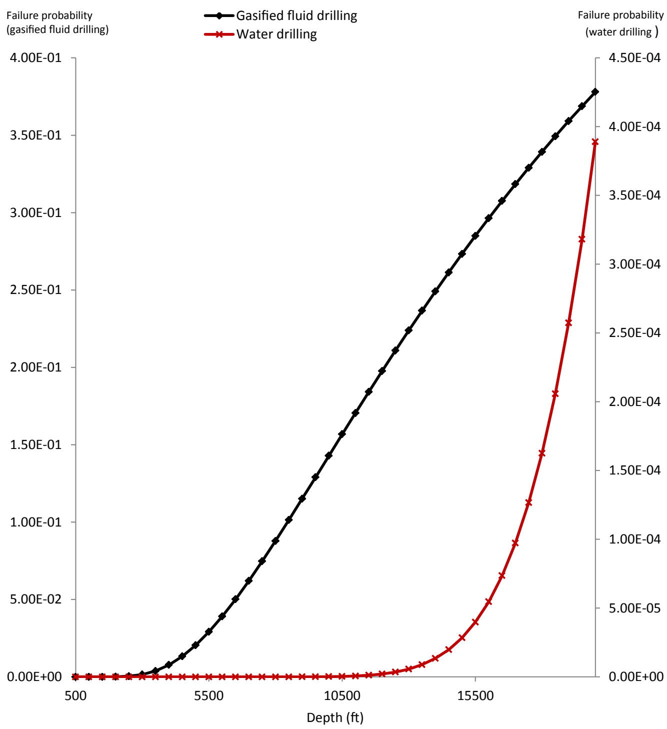


**Fig. 6.** Failure probabilities of RCD as a function of depth and mud density.

**Table 4**
Prior failure probabilities of the safety barriers.

| Safety Barrier, $SB_i$ | Ignition Prevention Barrier (IPB) | Escalation Prevention Barrier (EPB) | Damage Control and Emergency Management Barrier (DC&EMB) |
|---|---|---|---|
| Failure probability,$p(SB_i)$ | 2.72E-02 | 8.60E-03 | 1.50E-03 |

**Table 5**
Accident precursor data (cumulative) from a UBD operation over a period of 24 h towards the major accident (catastrophe).

| Hour | Vapor cloud/Oil spill | VCE/Pool fire | Secondary Explosion/Fire | Catastrophe |
|---|---|---|---|---|
| 1 | 1 | – | – | – |
| 2 | 1 | – | – | – |
| 3 | 2 | 1 | – | – |
| 4 | 2 | 1 | – | – |
| 5 | 2 | 1 | – | – |
| 6 | 3 | 1 | – | – |
| 7 | 3 | 1 | – | – |
| 8 | 4 | 1 | – | – |
| 9 | 5 | 2 | – | – |
| 10 | 6 | 2 | – | – |
| 11 | 6 | 2 | – | – |
| 12 | 7 | 2 | – | – |
| 13 | 7 | 2 | – | – |
| 14 | 8 | 2 | – | – |
| 15 | 9 | 2 | – | – |
| 16 | 10 | 3 | – | – |
| 17 | 10 | 3 | – | – |
| 18 | 11 | 3 | – | – |
| 19 | 11 | 3 | – | – |
| 20 | 11 | 3 | – | – |
| 21 | 12 | 4 | – | – |
| 22 | 13 | 5 | 1 | – |
| 23 | 14 | 6 | 2 | – |
| 24 | 15 | 7 | 3 | 1 |

**Table 6**
Prior occurrence probabilities of consequences.

| Vapor cloud/Oil spill | VCE/Pool fire | Secondary explosion/Fire | Catastrophe |
|---|---|---|---|
| 5.64E-03 | 1.56E-04 | 1.35E-06 | 2.04E-09 |

**Table 7**
Posterior (updated) failure probabilities of safety barriers.

| Hour | IPB | EPB | DC&EMB |
|---|---|---|---|
| 1 | 2.72E-02 | 8.60E-03 | 1.50E-03 |
| 2 | 2.72E-02 | 8.60E-03 | 1.50E-03 |
| 3 | ***1.38E-02*** | 8.60E-03 | 1.50E-03 |
| 4 | ***1.38E-02*** | 8.60E-03 | 1.50E-03 |
| 5 | ***1.38E-02*** | 8.60E-03 | 1.50E-03 |
| 6 | ***9.23E-03*** | 8.60E-03 | 1.50E-03 |
| 7 | ***9.23E-03*** | 8.60E-03 | 1.50E-03 |
| 8 | ***6.94E-03*** | 8.60E-03 | 1.50E-03 |
| 9 | ***1.11E-02*** | 8.60E-03 | 1.50E-03 |
| 10 | ***9.23E-03*** | 8.60E-03 | 1.50E-03 |
| 11 | ***9.23E-03*** | 8.60E-03 | 1.50E-03 |
| 12 | ***7.93E-03*** | 8.60E-03 | 1.50E-03 |
| 13 | ***7.93E-03*** | 8.60E-03 | 1.50E-03 |
| 14 | ***6.94E-03*** | 8.60E-03 | 1.50E-03 |
| 15 | ***6.18E-03*** | 8.60E-03 | 1.50E-03 |
| 16 | ***8.32E-03*** | 8.60E-03 | 1.50E-03 |
| 17 | ***8.32E-03*** | 8.60E-03 | 1.50E-03 |
| 18 | ***7.57E-03*** | 8.60E-03 | 1.50E-03 |
| 19 | ***7.57E-03*** | 8.60E-03 | 1.50E-03 |
| 20 | ***7.57E-03*** | 8.60E-03 | 1.50E-03 |
| 21 | ***9.23E-03*** | 8.60E-03 | 1.50E-03 |
| 22 | ***1.27E-02*** | ***1.73E-03*** | 1.50E-03 |
| 23 | ***1.57E-02*** | ***2.88E-03*** | 1.50E-03 |
| 24 | ***2.01E-02*** | ***4.93E-03*** | ***5.01E-04*** |

the 23rd hour is due to insufficient data at the 24th hour. A similar explanation holds for the risk profiles presented in Figs. 9 and 10 from Table 9.

## 4. Conclusion

This study has proposed a bow-tie model for real time risk analysis of drilling operations. The bow-tie, qualitatively, illustrates

**Table 8**
Occurrence frequencies of consequences/end events.

| Hour | Vapor cloud/Oil spill | VCE/pool fire | Sec. Explosion/Fire | Catastrophe |
|---|---|---|---|---|
| 1 | 5.64E-03 | 1.56E-04 | 1.35E-06 | 2.04E-09 |
| 2 | 5.64E-03 | 1.56E-04 | 1.35E-06 | 2.04E-09 |
| 3 | 5.72E-03 | 7.93E-05 | 6.87E-07 | 1.03E-09 |
| 4 | 5.72E-03 | 7.93E-05 | 6.87E-07 | 1.03E-09 |
| 5 | 5.72E-03 | 7.93E-05 | 6.87E-07 | 1.03E-09 |
| 6 | 5.75E-03 | 5.31E-05 | 4.60E-07 | 6.91E-10 |
| 7 | 5.75E-03 | 5.31E-05 | 4.60E-07 | 6.91E-10 |
| 8 | 5.76E-03 | 3.99E-05 | 3.46E-07 | 5.19E-10 |
| 9 | 5.74E-03 | 6.36E-05 | 5.51E-07 | 8.28E-10 |
| 10 | 5.75E-03 | 5.31E-05 | 4.60E-07 | 6.91E-10 |
| 11 | 5.75E-03 | 5.31E-05 | 4.60E-07 | 6.91E-10 |
| 12 | 5.75E-03 | 4.56E-05 | 3.95E-07 | 5.93E-10 |
| 13 | 5.75E-03 | 4.56E-05 | 3.95E-07 | 5.93E-10 |
| 14 | 5.76E-03 | 3.99E-05 | 3.46E-07 | 5.19E-10 |
| 15 | 5.76E-03 | 3.55E-05 | 3.08E-07 | 4.62E-10 |
| 16 | 5.75E-03 | 4.78E-05 | 4.14E-07 | 6.22E-10 |
| 17 | 5.75E-03 | 4.78E-05 | 4.14E-07 | 6.22E-10 |
| 18 | 5.76E-03 | 4.35E-05 | 3.77E-07 | 5.66E-10 |
| 19 | 5.76E-03 | 4.35E-05 | 3.77E-07 | 5.66E-10 |
| 20 | 5.76E-03 | 4.35E-05 | 3.77E-07 | 5.66E-10 |
| 21 | 5.75E-03 | 5.31E-05 | 4.60E-07 | 6.91E-10 |
| 22 | 5.73E-03 | 7.38E-05 | 1.28E-07 | 1.92E-10 |
| 23 | 5.71E-03 | 9.09E-05 | 2.63E-07 | 3.94E-10 |
| 24 | 5.68E-03 | 1.16E-04 | 5.75E-07 | 2.88E-10 |

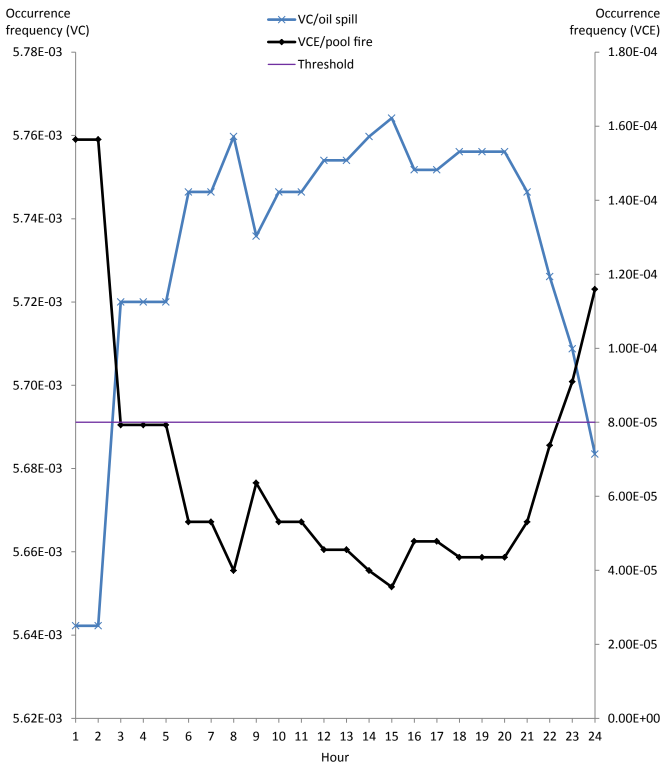


**Fig. 7.** Occurrence frequency profiles for VC/oil spill and VCE/pool fire end events.

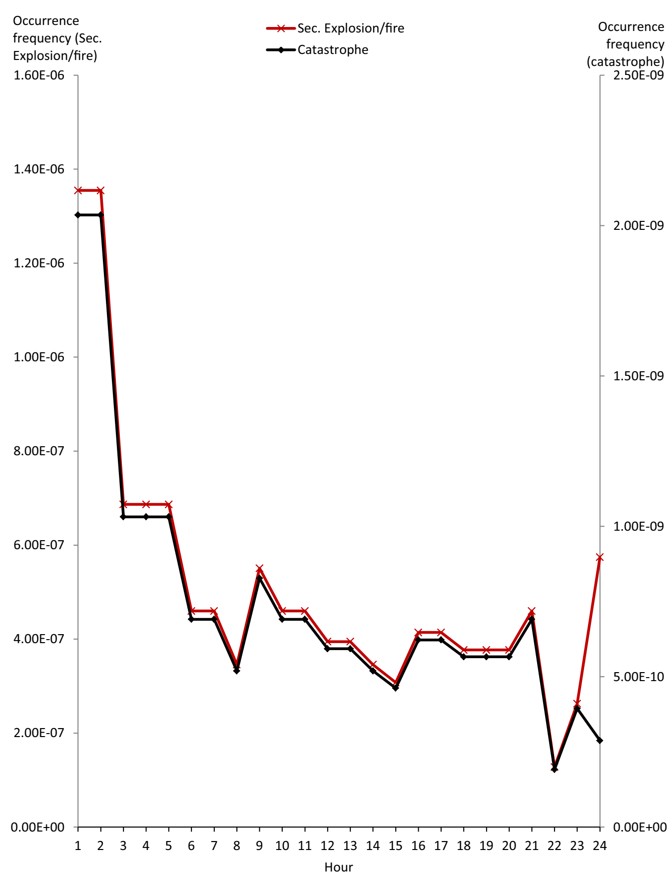


**Fig. 8.** Occurrence frequency profiles for secondary explosion/fire (Sec. Explosion/fire) and Catastrophe consequences.

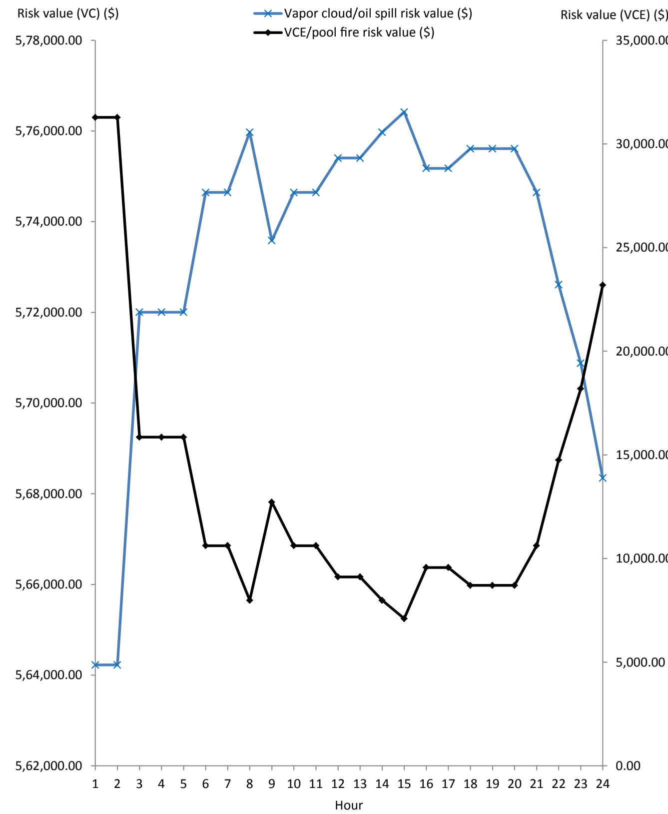


**Fig. 9.** Risk profiles for VC/oil spill and VCE/pool fire consequences.

the logical relationships between the components of the drilling operations and the consequences through the safety barriers. Quantitatively, it links the failure probabilities of the components and the safety barriers to the frequencies of the consequences. A predictive failure probabilistic model also has been proposed for

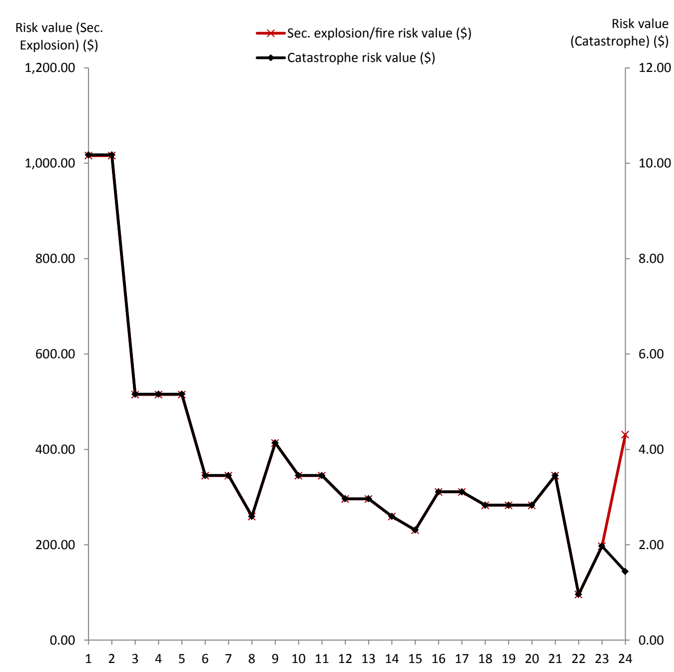


**Fig. 10.** Risk profiles for Secondary (Sec.) explosion/fire and Catastrophe consequences.

**Table 9**
Risk Profile of the end events in USD over the 24-h period.

| Hour | Vapor cloud/Oil spill risk value ($) | VCE/pool fire risk value ($) | Sec. explosion/fire risk value ($) | Catastrophe risk value ($) |
|---|---|---|---|---|
| 1 | 564,224.00 | 31,280.65 | 1016.03 | 10.18 |
| 2 | 564,224.00 | 31,280.65 | 1016.03 | 10.18 |
| 3 | 572,003.24 | 15,855.97 | 515.02 | 5.16 |
| 4 | 572,003.24 | 15,855.97 | 515.02 | 5.16 |
| 5 | 572,003.24 | 15,855.97 | 515.02 | 5.16 |
| 6 | 574,644.22 | 10,619.45 | 344.93 | 3.45 |
| 7 | 574,644.22 | 10,619.45 | 344.93 | 3.45 |
| 8 | 575,973.87 | 7983.02 | 259.30 | 2.60 |
| 9 | 573,584.91 | 12,719.85 | 413.15 | 4.14 |
| 10 | 574,644.22 | 10,619.45 | 344.93 | 3.45 |
| 11 | 574,644.22 | 10,619.45 | 344.93 | 3.45 |
| 12 | 575,403.26 | 9114.41 | 296.04 | 2.96 |
| 13 | 575,403.26 | 9114.41 | 296.04 | 2.96 |
| 14 | 575,973.87 | 7983.02 | 259.30 | 2.60 |
| 15 | 576,418.45 | 7101.49 | 230.66 | 2.31 |
| 16 | 575,175.34 | 9566.34 | 310.72 | 3.11 |
| 17 | 575,175.34 | 9566.34 | 310.72 | 3.11 |
| 18 | 575,610.62 | 8703.25 | 282.69 | 2.83 |
| 19 | 575,610.62 | 8703.25 | 282.69 | 2.83 |
| 20 | 575,610.62 | 8703.25 | 282.69 | 2.83 |
| 21 | 574,644.22 | 10,619.45 | 344.93 | 3.45 |
| 22 | 572,610.54 | 14,753.32 | 95.84 | 0.96 |
| 23 | 570,878.82 | 18,189.77 | 196.94 | 1.97 |
| 24 | 568,346.41 | 23,192.23 | 430.89 | 1.44 |

determining failure probabilities of basic components of during drilling operations. The dynamic model is capable of updating the failure probabilities of the components of the bow-tie, thus, overcoming the static nature of common risk assessment techniques. This study has identified key components of drilling operations as shown in the fault trees.

Different drilling techniques such as COBD and UBD are compared. In COBD, the components are the drilling mud, riser and its components, choke and kill lines, failsafe valves, and the BOP. While in UBD, in addition to those listed for COBD, the most important component is RCD. Others are a dedicated choke manifold, drill-pipe non-return valve and snubbing unit.

A well designed RCD capable of withstanding prevailing pressures will ensure safe application of UBD in harsh environments. The results from the comparative analysis of COBD and UBD shows that if the RCD is well designed and selected UBD could be made safer than COBD as the occurrence probability of COBD tripled that of UBD during drilling.

The event tree is updated through Bayes theorem by utilizing the accident precursors information collected during the drilling operation. The threshold frequency of the end event(s) determined is/are compared with the posterior frequencies to determine whether to continue drilling or review the existing condition to avoid accident. Thus, the drilling operation is effectively managed, non-productive time is minimized and accidents could be prevented. Through a case study, it was clearly shown that by using accident precursors in risk updating, the drilling operation would have been halted at the 22nd h, thus, preventing the catastrophic event that was likely to occur at the 24th hour. This methodology can be integrated into a real time risk monitoring device for field application during drilling operations.

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