Development of the Extended BOP Retrieval Decision Tool

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ABSTRACT

In this paper, we present the initial formulation of a hybrid model incorporating both time-dependent reliability and Bayesian Network methods to develop a tool that is capable of capturing most of the important factors related to the subsea well safety problem. An overall model for the drilling well safety problem is developed by constructing a Bayesian network model that incorporates all factors that influence the probability of a blowout during a drilling campaign. The probabilities of failure on demand (PDFs) of the BOP safety functions are calculated by a time-dependent reliability model and provided as input to the BN. The key indicators evaluated by the model are the probabilities of: kick, loss of well control and of a blowout. The model is then calibrated for a typical drilling well considering the full range of possibilities of the important parameters. baseline values are obtained which form the prior distribution for the typical well. When first applied to a specific well, the evidences pertaining to that well are input to the model and new values are calculated. Throughout the drilling campaigns, evidences of changes of important factors are sensed by various means. Whenever an important management decision needs to be made, evidences of the current situation are fed to the tool which calculates new values of the key parameters and displays them in colour graphics.

1. INTRODUCTION

The detection of the failure of any of the components of BOP while the equipment is on the sea bottom and the drilling process is under way brings about a very serious decision to the drillers and operators: do we have to stop the drilling process and immediately pull the BOP up for repair or can we continue drilling with a degraded BOP? This is a typical case of an operational risk where a risk-based decision must be taken after a degradation of the current operating condition is detected.

Models for the time-dependent reliability evaluation of safety systems have already been developed and applied to advanced tools for decision making related to this BOP retrieval problem [1, 2]. Despite giving a stronger basis for decision making compared to what previously existed, only the conditions of the BOP itself were considered. Drillers and operators alike have indicated that they need to take other factors into account when taking this decision.

In this paper, we present the initial formulation of a hybrid model incorporating both time-dependent reliability and Bayesian network methods to develop a tool that is capable of capturing most of the important factors related to the subsea well safety problem. Firstly, an overall model for the well safety problem is generated using Bayesian network. The key indicators evaluated by the model are the probability of a kick, the probability of loss of well control and the probability of a blowout, all within the time span of an established drilling campaign. The model is then calibrated for a typical drilling well considering the full range of possibilities of the parameters which are important for the calculation of the referred key indicators. At this point baseline values are obtained which are called recertification values (prior distribution). When first applied to a specific drilling well, the evidences pertaining to that specific well are then given as input to the model and new values are calculated which are named the normal values.

2. OBJECTIVES OF THIS WORK

Throughout the drilling campaigns, evidences of changes of important factors (most probably degradation, including failures of BOP components) are sensed by various means. The main objective of this paper is to present the basic concepts of a comprehensive tool to help managers to make better decisions related to the need to retrieve the BOP from the bottom of the sea upon detecting a failure of one of its components during the drilling process. This tool is the continuation of the development of the BOP-RDT previously developed by DNV GL [3]. This extended tool takes into account not only the impact of the detected failure on the PFD of the BOP safety functions but also the effects of any new evidences of any other factor which may influence the probability of a blowout during the current drilling campaign.

Any time an important management decision needs to be made related to the retrieval of the BOP during the drilling campaign, the evidences of the current situation are fed to the tool which calculates new values of the key parameters (posterior distributions) and displays them in color graphs. A color scheme is used to alert management of the degradation of the safety conditions of the drilling operation. This is done by comparing the variation of the key indicators for the degraded conditions with those of the normal and recertification values. The number of factors included in the Bayesian network model is very large, including the following (among many others): reservoir characteristics, well conditions, human factors, and BOP safety functions. The latter are run after information of a component failure is passed to the time-dependent reliability model and the results are directly fed to the Bayesian network model.

3. DESCRIPTION OF THE WORK

In this paper, time-dependent reliability and Bayesian Network (BN) methods are used in combination to develop a tool that can capture most of the important factors related to the subsea well safety problem. This model adds a new dimension to the BOP retrieval decision by incorporating other important factors besides the degradation of the PFDs of the BOP safety functions.

3.1 – WELL RISK INDICATORS

The main risk during drilling of an oil well derives from the possibility of occurrence of a blowout. A blowout is an uncontrolled flow of hydrocarbons from a well to the surrounding environment. There are two main types of blowouts: surface and underground. The former is considered the most dangerous type as it can lead to fires and explosions in the drilling rig with the consequent loss of lives, in addition to large spills, such as the one in Deepwater Horizon rig in Macondo field [4]. In addition to technical integrity, the correct operation of the BOP safety functions plays a major role in the prevention of surface blowouts.

Normally, a blowout is preceded by a kick, which is an unwanted influx of formation fluids into the wellbore as a result of a pressure imbalance (the pressure of formation fluids exceeds the pressure exerted by the column of drilling fluid). A kick can result in a blowout if it is not detected and controlled in a timely manner. In this paper the risk of a surface blowout is modeled as a combination of three main factors: the occurrence of a kick (the initiating event), the response of the control system to contain the kick, and ultimately, the response of the BOP safety functions to prevent the effects of the uncontrolled kick from reaching the surface. The ensemble of these factors comprises the well safety barriers which are defined in the D-010 Standard [5] as “the envelope of one or several dependent barrier elements preventing fluids or gases from flowing unintentionally from the formation, into another formation or to surface”. Therefore, our model looks at the effects of detected failures of BOP components on the degradation of the overall integrity of the well and not only on the increase of the PFDs of the BOP safety functions.

3.2 – BAYESIAN NETWORK

Firstly, an overall model for the well safety problem is generated using a Bayesian Network (BN). A basic reference to this work is that of Bolsover [6].

A BN is an acyclic directed graph, which is represented by a diagram with nodes and arcs. The nodes represent the variables that are important to the problem being analyzed and the arcs show the causal/influential relationship between the variables. For each node, a conditional probability table is specified, which consider the probability of the variable being in different states conditioned on the states of the other variables on which this variable depends. BN can be used to make inference in both directions: forward by predicting the probability of outcomes and reverse inference diagnose of probable causes of each outcome.

The evidences on the variables related to the well conditions at the current date can be combined with the BOP SFs PFDs, considering the current detected BOP failures using the BN to evaluate the current drilling campaign blowout probability.

The BOP Safety Functions status are evaluated using the BOP RDT [3], which evaluates the BOP safety functions probability of failure on demand as function of time and gives a prediction of the average BOP SFs PFDs up to the end of current campaign based on the BOP status. Then, the obtained average values of BOP SFs PFDs are used in the BN to evaluate the interaction with the current well conditions.

The BN was built using Genie 2.0, which is provided by Decision Systems Laboratory, University of Pittsburgh (Genie 2.0 1998-2013) [7]. This network is structured in sub models to facilitate the visualization (Figure 1). Kick occurrence can be due to the following grouped causes:

- Reservoir Conditions;

- Drilling Operation Conditions;
- Drill String Operations;
- Well Designs Problems;
- Mud Mix Problems.

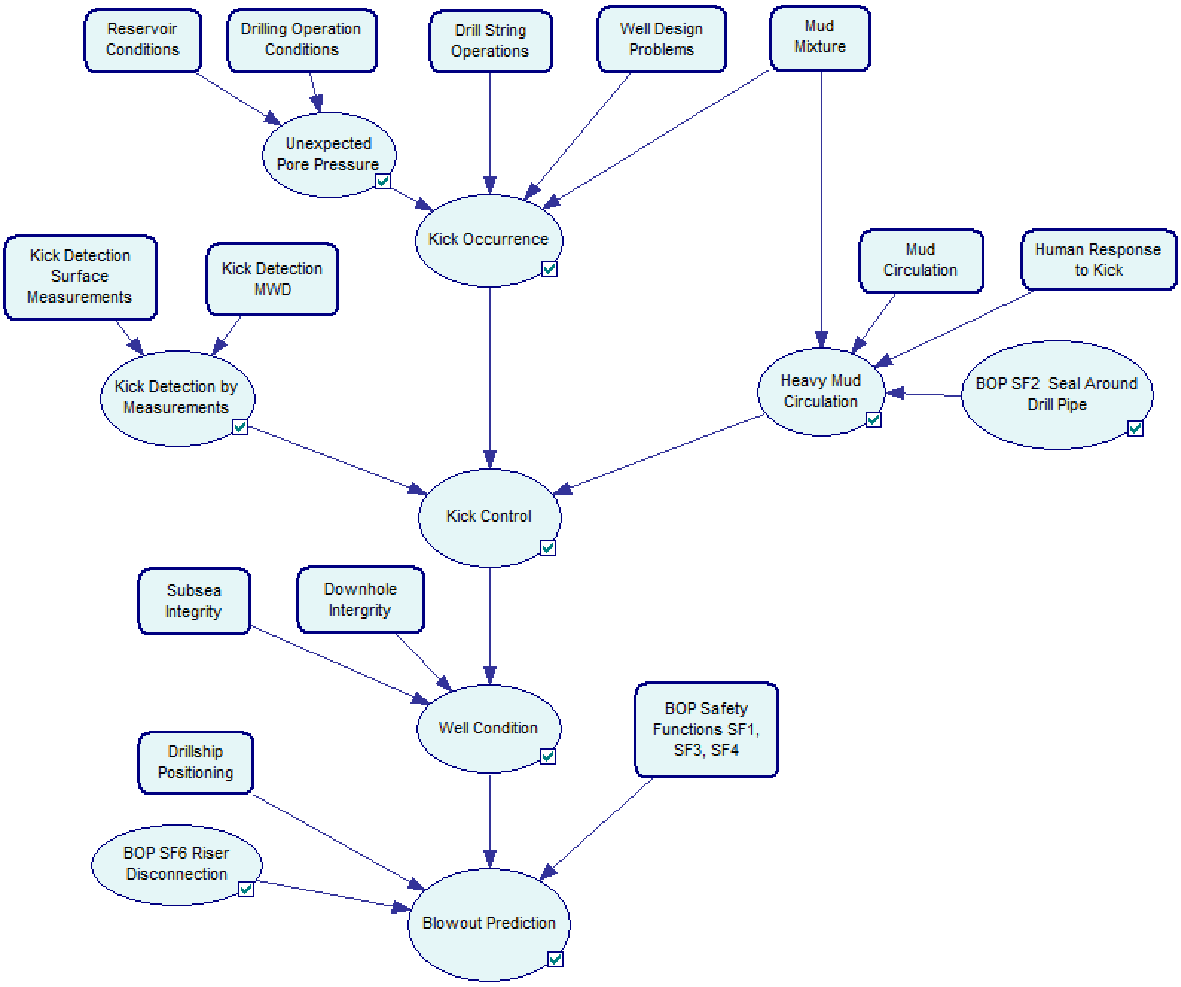


Figure 1 - Well Condition Bayesian Network

The kick detection measurements were grouped into: a) surface measurements, and b) measurements while drilling – MWD.

If a kick occurs, it should be detected and controlled by heavy mud circulation. Therefore, the loss of well control can happen if the kick is not detected or if the heavy mud circulation fails. The kick control is conditional on kick occurrence, kick detection by measurements and heavy mud circulation. The heavy mud circulation to control a kick depends on mud mixture composition, mud circulation, the human response to a kick and the BOP Safety Function SF2 to seal around the drill pipe.

In case of subsea loss of integrity due to external leakage in the riser, in the LMRP (Lower Marine Riser Package) or in the LMRP connector, BOP would be used to close the well to avoid a loss of control. After closing the BOP, the riser would be disconnected and pulled out for repair. Therefore, in this situation the required BOP SFs are the same as the case of an emergency disconnection in case of drillship loss of position.

In case of leak in the BOP or in the wellhead connector, the well should be plugged and the BOP would have to be retrieved for repair. Whenever the BOP must be retrieved, the drill pipe will be pulled out, the well will be plugged and the BOP will be disconnected from the wellhead by opening the wellhead connector.

In case of downhole loss of integrity, such as casing or connections leaks or cement shoe failures, the BOP could be used to close the well. These failures do not involve the decision to pull out the BOP or not, but they contribute to the blowout probability.

The historic mean average kick occurrence for deep water given by Holand & Awan [8] is 0.360 kicks/ exploratory well and 0.132 kicks/development well. From Ref. [9], the surface blowout average frequency for an exploratory well is equal to one in 714 wells drilled (1.40E-03 blowout/exploratory well). For a development well, the surface blowout average frequency is one in 3623 wells drilled (2.76E-04 blowout/ development well).

3.3 – THE BOP SAFETY FUNCTIONS

Considering that the riser would continue to be connected to the wellhead (no drilling rig loss of position), the following BOP SFs could be required according to the drilling condition:

- Riser Stay Connected - Drill Pipe Through the BOP:
  SF1: Shear drill pipe and seal off well - Cutting by Blind or Casing Shear Rams and Closing and Locking by Blind Shear Ram.
  SF2: Seal around drill pipe - Closing the Annular Preventers or the Pipe Rams.
- Riser Stay Connected - Casing Through the BOP:
  SF3: Shear casing and seal off well - Cutting by Casing Shear Ram and Closing and Locking by Blind Shear Ram.
- Riser Stay Connected - Open Hole:
  SF4: Seal off open hole - Closing and Locking by Blind Shear Ram.

Usually the SF2 is required to control a kick. The SF1 is required when the kick control fails with the drill string inside the BOP, which is the most frequent configuration (typically 86% of the drilling campaign). The SF3 is required only when a kick control fails while is running the casing (usually 4% of drilling campaign time). The SF4 is required when there is no drill string through the BOP (typically 10% of the drilling campaign). If the remaining drilling interval will have only the drill string inside the BOP, then the required SFs would be only SF2 to control the kick and SF1 in case of kick control failure.

The BOP SFs can be also required due to drillship loss of position requiring use of the Emergency Disconnection System (EDS). It is being considered that a drillship can lose its position due to:

– Bad weather occurrence with environmental conditions above the Dynamic Positioning (DP) system capability, requiring the drillship to disconnect when the riser angle limit is reached (red zone), excessive heave or excessive thruster force.
– Drillship drift-off due to DP system failures.
– Drillship drive-off due to DP system failures.

When the Emergency Disconnection System is activated by the operator from the Driller Control Panel (DCP) or from the Toolpusher Control Panel (TCP), the LMRP connector is opened, which open the Auto Shear Valve (ASV) which activates the Automatic Mode Function (AMF) to close the BSR or the CSR and the BSR.

In this situation, if the BOP fails to close the well or LMRP connector fails to unlock, both the primary and secondary barriers may be lost and a blowout can occur. This situation does not involve the decision to pull out the BOP or not, but it contributes to the blowout probability. In this case the following BOP SFs could be required according to the drilling condition:

- Emergency Disconnection - Drill Pipe Through the BOP:
  SF1: Shear drill pipe and seal off well - Cutting by Blind or Casing Shear Rams and Closing and Locking by Blind Shear Ram.
  SF6: Disconnect the riser by opening the LMRP connector
- Emergency Disconnection -- Casing Through the BOP:
  SF3: Shear casing and seal off well - Cutting by Casing Shear Ram and Closing and Locking by Blind Shear Ram.
  SF6: Disconnect the riser by opening the LMRP connector
- Emergency Disconnection - Open Hole:
  SF4: Seal off open hole - Closing and Locking by Blind Shear Ram.
  SF6: Disconnect the riser by opening the LMRP connector

3.4 – PROPOSED MANAGEMENT DECISION CONDITIONS

From the input of the well variables and parameters states and from the BOP RDT SFs PFDs evaluation, the BN updates the blowout prediction probability. This probability should be compared with a criterion to help in the decision process. The criterion can be chosen by the operator based on his tolerability criteria for the probability of occurrence of a blowout.

As the BOP can be used in different wells conditions and campaigns, the BN was built using the recertification BOP SFs PFDs values. The blowout probability obtained before any well data input, considering only the recertification BOP SFs PFDs and the generic data is called the recertification blowout probability. This probability is used as a reference for comparison with the others (normal, and degraded).

The normal blowout probability is obtained for the well that is being drilled considering the current well data evidences and the normal values of the BOP SFs PFDs (without any BOP failure).

The blowout probability for the condition of a degraded BOP is obtained considering the current well data evidences and the degraded values of the BOP SFs PFDs (with BOP failure).

All the recertification values are in blue color. The normal blowout probability can be in a green, yellow, orange or red color. The degraded and delayed blowout probability can be in a yellow, orange or red color. The kick occurrence and the loss of well control probabilities color are the same of the blowout probabilities.

Below is a set of suggested values for the color schemes. Other criteria may of course be used.

Green State: – blowout probability increases up to 20%

This is the normal state where everything is operating as expected. Well conditions are stable, there is no detected failure on the BOP and the blowout probability is within the mean value for the well under normal conditions. As the blowout probability mean value is equal to the well normal value, the drilling operation can continue. Depending on the well conditions and characteristics, without any failure or degradation, the normal blowout probability was allowed in this model to be above the recertification blowout probability by up to 20%. Therefore, in this state, the average normal blowout probability is up to 1.2 of the average recertification blowout probability. This state exists only when there is no BOP failure (normal blowout probability).

Yellow State: – blowout probability increases up to 50%

In this state the BOP can be in a degraded status and the probability of blowout occurrence may have increased up to 50% of its recertification value. If the average normal blowout probability is above 20% and below 50% of the average recertification blowout probability, the condition is called a yellow state. Even if the resulting blowout probability caused by a detected failure of the BOP is less than 20% of the normal probability, the state will be indicated as yellow, meaning that there is no green state if a BOP component failure is detected, independently of the value of the resulting blowout probability.

Orange State: – blowout probability increases from 50% up to 200%

In this state the BOP can be degraded and the probability of blowout occurrence increased above 50% of its recertification value, but the increase is lower than 200% of its recertification value. There is a detected failure of a BOP component and the well conditions may have changed a bit, but there is no prediction of a kick by the kick measurement variables. The BOP SFs PFDs are degraded and the blowout probability mean value is up to 3 times that of its recertification value. If the BOP Safety Functions probabilities are all below 1.0e-01 (SIL 1) and the blowout probability increases up to 3 times due to well condition, then the BOP cannot be retrieved before the well is brought to a controlled state. After bringing the well under control, the operator can decide if the BOP will be retrieved for repair or not.

Red State: – blowout probability increases above 200%

In this state the BOP can be degraded and the probability of blowout occurrence increased above 200% of its recertification value. If there is a detected failure on the BOP and well conditions are stable, then the drilling operation could be interrupted, the well closed and the BOP pulled out for repair. If the increase of the blowout probability above 3 times of its recertification value is due also to loss of well control, then the operator would try to use the available resources to control the well before deciding to retrieve the BOP for repair.

3.5 – EXAMPLE OF INPUT OF EVIDENCES

The key indicators evaluated by this combined model are the probability of a kick, the probability of loss of well control and the probability of a blowout, all within the time span of an established drilling campaign. This enhanced tool is called BOP ERDT – Blowout Preventer Extended Retrieval Decision Tool to make distinction from the BOP RDT.

The user enters the input data for BOP and run the BOP RDT to obtain the safety functions status. After running the BOP RDT for the current BOP status, the user can see the results for the BOP safety functions. In the screen of the quantitative summary of BOP RDT is presented a control button “Well Conditions” that open a screen that allows the user to specify the well conditions and evidences. When the user presses this button, the screen “Well Data Evidences” is opened, as shown in Figures 2.

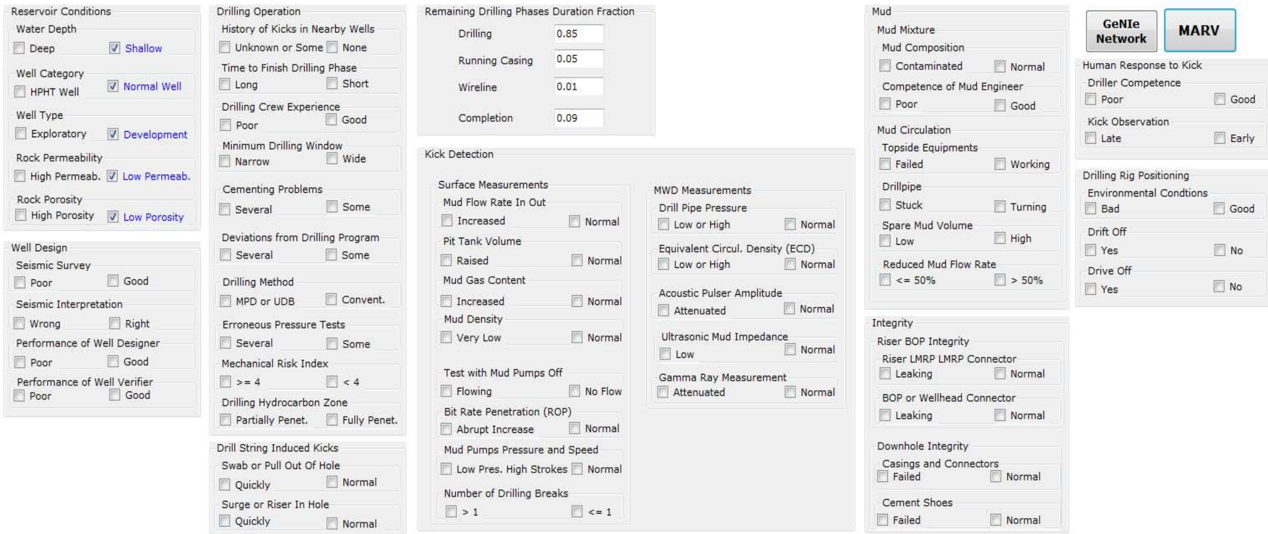


Figure 2 - Well Data Evidences Input Screen

In this screen the user can input the current well characteristics, the current drilling operations conditions, any kick measurement or other well evidence of failure or behavior different from the expected. The chosen evidences are shown in blue letters and are grouped in the following types:

- Reservoir Conditions
- Well Design
- Drilling Operation
- Drill String Induced Kicks
- Remaining Drilling Phases Duration Fraction
- Kick Detection
- Mud
- Integrity
- Human Response to Kick
- Drilling Rig Positioning

The remaining drilling phases duration fraction should be updated to reflect, for the remaining drilling campaign, what are the time fractions expected in each of the remaining drilling phases.

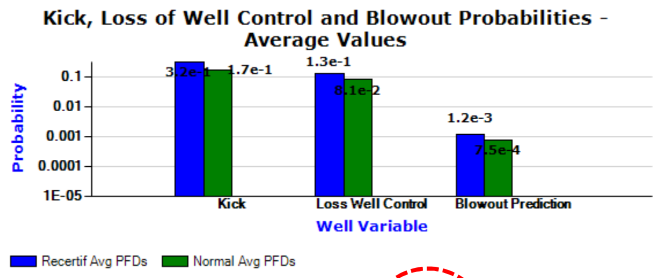
For each group the user specifies those variables that he has evidence for. After specifying the applicable evidences for the current drilling phase, the user should click the button “Update” to update the BN believes and get the probabilities of having a kick, a loss of well control and a blowout.

The kick occurrence, the loss of well control and the blowout probabilities are evaluated for the average values of the well data evidences and for average and maximum values of SFs PFDs. As the kick occurrence, does not depend on the BOP safety functions, the probability of kick occurrence obtained for the maximum values of SFs PFDs is equal to the one obtained for the average values of SFs PFDs. The loss of well control probability depends only on the SF2 PFD.

4. A WORKED CASE EXAMPLE

As an illustrative example, the model is applied for a shallow water normal development well with low permeability and low porosity with remaining drilling campaign from 15/11/2016 up to 21/02/2017.

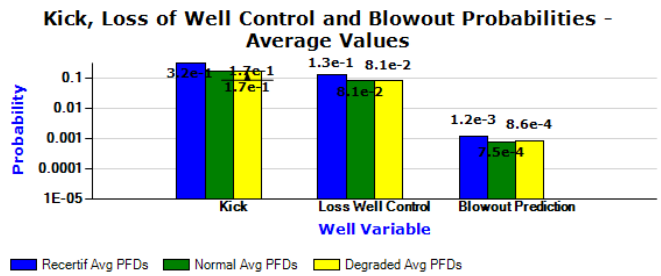
With the data used in this example, it can be seen from Figure 3 that for a generic development well with no evidences and no detected failures in the BOP, the average kick probability turns out to be equal to 0.32 (one kick at every 3.13 wells drilled) and the average loss of well control probability is equal to 0.13 (one in every 7.7 wells drilled). The average recertification blowout probability is equal to 1.2E-03 per drilled well or one blowout at every 833 wells drilled. For a remaining campaign duration of three months the average normal blowout probability is equal to 7.5E-04 /well.



Avg. Results	Avg. Kick	Avg. Loss of ...	Avg. Blowout
Recertif.	3.2E-1	1.3E-1	1.2E-3
Normal	1.7E-1	8.1E-2	7.5E-4
Degraded			
Delayed			

Figure 3 - Blowout Probability for a Development Well with No BOP Failures

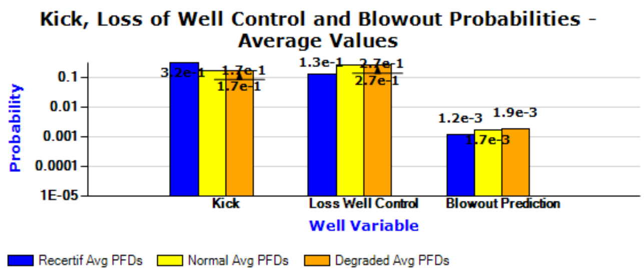
In case of failure in the BOP acoustic subsea system, after running the tool for this condition, the degraded BOP safety functions status changes to a yellow condition (not shown here) and the average degraded blowout probability is equal to 8.6E-04/well, corresponding also to a yellow condition, as shown in Figure 4. The impact of the detected failure is shown to be small (all SFs remain in the SIL 2 condition – see [3]) and therefore under such conditions, the operator will certainly decide to leave the BOP down and continue the drilling operation.



Avg. Results	Avg. Kick	Avg. Loss of ...	Avg. Blowout
Recertif.	3.2E-1	1.3E-1	1.2E-3
Normal	1.7E-1	8.1E-2	7.5E-4
Degraded	1.7E-1	8.1E-2	8.6E-4
Delayed			

Figure 4 - Development Well Blowout Probability after a detected BOP Acoustic System Subsea Failure

Let us consider now that some days after the decision to continue to drill with a detected failed acoustic system, mud circulation is lost. After updating the model with this information, it is obtained that the loss of well control probability has now increased from 8.1E-02 to 2.7E-01 and the degraded blowout probability goes from 8.6E-04 to 1.9E-03/well, as shown in Figure 5. Therefore, due to known degradation of the drilling process, the blowout probability goes from a yellow state to an orange state. In this situation, the operator cannot think of pulling out the degraded BOP but instead it is imperative to restore the mud circulation. Even though a little degraded, the BOP is the main line of defense if mud circulation cannot be restored.



Avg. Results	Avg. Kick	Avg. Loss of ...	Avg. Blowout
Recertif.	3.2E-1	1.3E-1	1.2E-3
Normal	1.7E-1	2.7E-1	1.7E-3
Degraded	1.7E-1	2.7E-1	1.9E-3
Delayed			

Figure 5 - Blowout Probability after a detected BOP Acoustic System Subsea Failure and Loss of Mud Circulation

5. CONCLUSIONS AND FINAL COMMENTS

The evaluation of the blowout probability is obtained by combining the PFDs of the BOP Safety Functions with the well conditions based on surface parameters and Measurement While Drilling (MWD) tools, the reservoir and drilling parameters and the operator response to a kick.

The probabilities of failure on demand of BOP SFs to close the well are evaluated considering BOP tests and on line diagnostic system and are given as inputs to the BN model.

When everything is normal the BN gives the expected probabilities of having a kick, a loss of well control and a blowout within the time frame of a drilling campaign. If the current evidences changes, then the probabilities are updated considering the changes. The BN is also updated whenever a failure is detected in the BOP or when the well condition variables or parameters change to an abnormal state.

Therefore, this decision support system takes into consideration not only the current BOP reliability status, but also the current well and drilling conditions in the evaluation of the blowout probability during the remaining drilling well campaign. These risk indicators may then be used to inform the decision about the need to immediately retrieve the BOP for repair or to continue drilling with a degraded BOP.

6. REFERENCES

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