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Risk-based safety analysis of well integrity operations

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ABSTRACT

Assurance of well integrity is critical and important in all stages of operation of oil and gas reservoirs. In this study, well integrity is modeled during casing and cementing operations. Two different approaches are adapted to model potential failure scenarios. The first approach analyzes failure scenarios using bow-tie model which offers a better visual representation of the logical relationships among the contributing factors through Boolean gates. The second approach takes advantage of Bayesian network, both to model conditional dependencies and to perform probability updating. The analysis identified managed pressure drilling system, logging tool, slurry formulation, casing design, casing handling and running method, surge and swab pressures as critical elements of the well integrity model. A diagnostic analysis on the slurry formulation further identified pilot test(s) and the interpretation of the test(s) as key elements to ensuring integrity of cementing operation. Relevant safety functions and inherent safety principles to improve well integrity operations are also explored.

1. Introduction

Well integrity relies on the application of technical, operational and organizational techniques to reduce the risk of uncontrolled release of formation fluids throughout the entire life cycle of a well (NORSOK, 2004). The operations of well integrity during drilling operations include the casing and cementing of drilled wellbore. Studies conducted by Danenberger (1993) and Izon et al. (2007) on blowouts in the Outer Continental Shelf of the U.S. between 1971 and 2006 (Fig. 1) identified casing failure and cementing as prominent contributing factors. Most of the investigatory reports on the causes of Macondo well blowout on April 20, 2010 attribute failures in the cementing operations to the accident (DHSG, 2011; CCR, 2011; BOEMRE, 2011; BP, 2010). The study of some of the factors which influence drilling ahead operations can be found in Abimbola et al. (2014, 2015a). Safety and risk analysis of casing and cementing operations are studied in the present work. Safety analysis of process systems and the assessment of their risks are often quantified using quantitative risk analysis techniques. Quantitative risk analysis has been expressed as the systematic identification and quantification of hazards to predict their effects on the individuals, property or environment (Skogdalen and Vinnem, 2012). Among the quantitative risk analysis tools, those commonly used are: fault tree analysis, event tree analysis, bow-tie, Failure Mode and Effect Analysis (FMEA) and Bayesian network. Fault tree analysis is widely recommended for its simple and effective approach in estimating the frequency or probability of critical events in a deductive process (Deshpande, 2011; Eskesen et al., 2004). However, it is incapable of handling multi-state variables and conditional dependencies, and performing probability updating as new information or evidence becomes available (Khakzad et al., 2011).

Event tree analysis and bow-tie have also been identified with similar characteristics (Ferdous et al., 2009, 2012). Consequently, variants of these methods have been developed that can be updated, such as the use of evidence theory to update the reliability data of rare events (Curcuru et al., 2012); use of fuzzy based reliability approaches for fault tree analysis (Purba, 2014); event tree analysis (Ferdous et al., 2009) and the resulting bow-tie (Ferdous et al., 2012, 2013). Recently, fault tree and bow-tie based models have been mapped into Bayesian network in dynamic risk analysis for dependability analysis and ease of updating mechanism (Khakzad et al., 2013b; Abimbola et al., 2015a). Further discussions on quantitative risk analysis in modeling accident scenarios and applicable quantitative risk analysis tools can be found in Khakzad et al. (2012) and Rathnayaka et al. (2013). This paper aims to achieve two main objectives. The first is to model and analyze casing and cementing operations as part of well integrity operations. From the analysis, safety critical elements of the operations will be identified. The second is to demonstrate the application of safety functions and inherent safety techniques to

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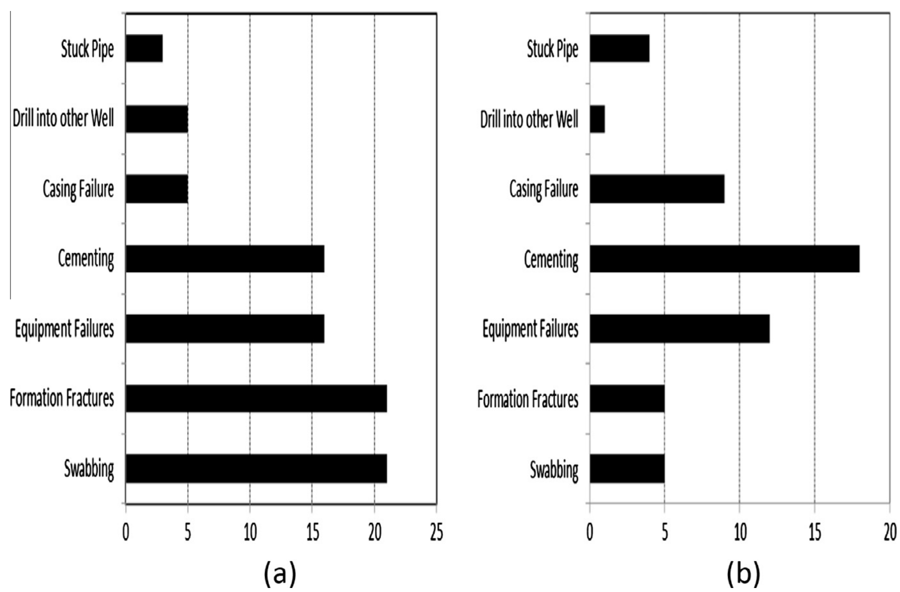

Fig. 1. Factors contributing to blowouts, (a) 1971–1991 and (b) 1992–2006 (Danenberger, 1993; Izon et al., 2007).

the well integrity operations in order to improve the reliability of the operations. The critical nature of cementing operation toward ensuring the integrity of the well is discussed in Section 2. Safety analysis techniques and the methodology adopted for this study are presented in Section 3. Section 4 presents the models of this study while the analysis is detailed in Section 5. Section 6 is devoted to the conclusion from the study.

2. Critical nature of cementing operation

During casing and cementing operations, liners are used for isolation of lost circulation and abnormally pressured zones so as to permit drilling ahead (drilling liner); covering up worn out or damaged section of an existing casing or liner (stub liner); and casing-off of the production interval of a well (production liner). It is very difficult, in practice, to obtain a good cement job on a liner. This is because of the small annular clearance between the liner and the open hole section; leading to difficulty in running (due to surge pressure) and centralizing the liner in the narrow open hole section across the producing zone; difficulty in achieving a good cement placement in the small annular clearance; and high tendency of lost circulation problems due to high pressure drop when circulating around the liner. The cement slurry for this section is often prone to contamination by the drilling mud; and there is often a difficulty in achieving an adequate liner movement for good cement placement. Thus, there is the need to investigate the critical nature of casing and cementing operations of the production zone.

3. Safety analysis techniques

3.1. Bow-Tie (BT)

Bow-tie is a risk analysis technique which combines a fault tree (FT) and an event tree (ET) with the top event of the FT as the initiating event of the ET. It is used to analyze the primary causes and consequences of an accident. A BT diagram (as shown in Fig. 2) presents the logical relationship between the causes, expressed as basic events (BEs) on one side, through intermediate events (IEs), top event (TE) and safety barriers (SBs) to the possible consequences (Cs) on the other side. For illustrative purpose, considering Fig. 2, the occurrence probability of end-event C_2 is given by

$$P(C_2) = P(TE) \cdot P(SB_1) \cdot P(1 - SB_2) \tag{1}$$

Similarly,

$$P(C_4) = P(TE) \cdot P(SB_1) \cdot P(SB_2) \cdot P(SB_3) \tag{2}$$

where $P(TE)$ is the probability of top event determined by the Boolean algebraic combination of the occurrence probabilities of the basic events, $P(BE_1), P(BE_2), \ldots$ and $P(BE_6)$. $P(SB_1)$, $P(SB_2)$ and $P(SB_3)$ represent the failure probabilities of the safety barriers SB_1, SB_2 and SB_3 respectively.

Bow-tie combines the advantages of FT and ET with its use found in many fields of science. Markowski and Kotynia (2011) used BT in a layer of protection analysis to model a complete accident scenario in a hexane distillation unit. Khakzad et al. (2012) applied BT in risk analysis of dust explosion accident in a sugar refinery. Forms of BT haven been applied in medical safety risk analysis (Wierenga et al., 2009) and analysis of hazard and effects management process of vehicle operations (Eslinger et al., 2004). Like its composites FT and ET, BT exhibits similar limitations and deficiencies of independency assumption and difficulty in its use for complex system analysis.

Forms of BT have been developed to integrate dynamic risk assessment into conventional static BT. This includes the incorporation of physical reliability models and Bayesian updating mechanism for risk analysis of process systems (Khakzad et al., 2012), offshore drilling operations (Abimbola et al., 2014), and a refinery explosion accident in which fuzzy set and evidence theory are used to assess uncertainties (Ferdous et al., 2013).

3.2. Bayesian network

Bayesian network is a directed acyclic graph in which nodes are random variables and directed arcs representing probabilistic dependencies and independencies among the variables. Bayesian network is a probabilistic method of reasoning under uncertainty (Abimbola et al., 2015b). Consider, for instance, the Bayesian network in Fig. 3 with binary nodes. A_1 is a root node without arcs directed into it while nodes A_3 and A_5 are leaf nodes without child nodes emanating from them. The root nodes are assigned with