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Characterization of Completion Operational Safety for Deepwater Wells

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Abstract. As the exploration and development of offshore energy resources moves into deeper waters, deepwater completion operations is facing much more challenging conditions than onshore and shallow water completion operations. Safety is one of the most important factors to be considered. In this paper, an integrated risk analysis model on basis of preliminary hazard analysis and Swiss cheese model is proposed to specifically evaluate both the static and dynamic risks involved during the deepwater completion phases. Uncertainties and potential hazards in deepwater completion operations and the corresponding consequences are identified by the proposed method. The safety degree of individual hazards is evaluated and effective measures are adopted to prevent, mitigate and control the deepwater completion accidents. Based on the above analysis, risk control model and six safety barriers including well structure barriers, correct operation barriers and well control barriers etc. will be established to mitigate and control incidents and major accidents caused by unintentional fluid leaking from the formation to surface. The greatest priviledge of this method is that it can be applied during the completion design and operation stages, where the effects of hazards in the process are unknown. Finally, a case study is presented to show how this method can be applied to the field operations.

Keywords: Completion operational safety deepwater wells preliminary hazard analysis safety barriers

1. Introduction

Deepwater drilling and completion operations have a great many uncertainties and potential hazards. Kick, blowout, borehole collapse, sand and other accidents is extremely likely to occur in the completing process, including reservoir drilling, cementing, perforating and testing **[1], [2]**. Blowout in deepwater completions can lead to wellbore scrapped, casualties and damage to ships. Risk analysis is required to mitigate the risk of casualties and property losses. Deepwater Horizon accident on the 20th of April 2010, resulting in 11 deaths and the huge economic losses more than 14 billion dollars, had raised serious concerns about the safety level of offshore drilling and completion. The investigation had shown that this accident was directly caused by the failure of annulus cement barrier and casing shoes barrier which could fail to isolate oil and gas [3]. There are 5 completion blowout accidents in Gulf of Mexico and the North Sea recorded in SINTEF offshore blowout database, which happened to occur at the same year [4]. Statistical blowout data has reflected that the blowout frequency is 1.2% and well leakage probability is 3.3% per 10000 wells completed in the North Sea [5]. The well completion phase could be considered as the weak link of multiple accidents in above researches. Therefore, hazards identification, risk assessment and mitigation measures concerned should be undertaken prior to the design stage of the completion. It is significant to attach great importance to strengthening safety barriers control in completion phase.

Given the above considerations, the primary emphasis of this article is to establish deepwater completion risk analysis model based on PHA and Swiss cheese model. The sequences will be illustrated explicitly, the

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related hazards of the deepwater completion can be identified, and risk causes, their potential consequences and risk levels of each operation are evaluated subsequently by this proposed model. In accordance with the above risk analysis, the safety barrier elements can be built to prevent, mitigate and control the development and consequence of the accidents and completion process safety will be guaranteed.

2. Overview of Deepwater Completion

According to the geological conditions and the types of oil and gas reservoirs, the greatest economic benefits of a oil and gas well can be obtained by choosing the most suitable completion way. The ways of the open hole gravel pack completion and casing gravel pack completion are widely considered in deepwater completion. Several detailed completion operational sequences are outlined in table 1, which may bring about accidents. Operation risks are evaluated on basis of previous experience and lessons learned from drilling risk assessment.

The objective of this paper focuses on the uncertainties and complexity of deepwater completion. There are some aspects of the completion architecture that have been affected by the nature of the deepwater environment. Several factors that are discussed in the table 2 have included environmental risks, shallow geological disasters, technical risk and operational risks.

Table. 1: Deepwater completion operation Sequences

Sequences	Deepwater completion operation
1	Drilling oil and gas layer
2	Down into the production casing
3	Cementing
4	install the BOP
5	killing pipeline and test pressure
6	Perforation
7	Gravel packing
8	Down into the production string
9	Install wellhead

Table. 2: Deepwater completion operation risk factors

Risks	Risks factors
Environmental risks	Typhoons, low temperature, soliton, water depth, high pressure, etc.
Shallow geological disasters	Shallow water and gas flowing, gas hydrates, the instability of seabed, abnormal high pressure sanding, corrosion by sour gas, etc.
Technical risk	Performance of drilling fluid, cementing quality, tubing testing, components materials, flow assurance, long-term integrity, reliability and maintainability equipment, such as SCSSV, etc.
Organizational risks	Process parameters monitoring, pressure, time, operational ways, competence, etc.

3. Risk Analysis Model

Risk assessment includes three steps: hazards identification, risk evaluation and mitigation measures. The identification and assessment for every procedure is one of the most important steps in a quantitative risk analysis. An integrated risk analysis model (Figure 1), preliminary hazard analysis and risk control model (PHA—RCM) proposed by this article, can realize comprehensive risk assessment from hazards identification to safety barriers establishment to reduce the possibility of undesired events. In this process, two types of risk assessment can be defined for high hazard operation:

1. An operations risk assessment (e.g. PHA) focuses on risk identification and the cause in relationship with hazards of individual operation involving the drilling oil and gas layer, cementing, gravel packing, perforating and oil and gas testing, etc.

2. An operations phase risk control (e.g. RCM) focuses definition and establishment of safety barriers to keep operation safe.

4. PHA

The PHA, probably the most commonly performed hazard analysis technique, is applicable to the risk analysis of all types of systems, facilities, operations, and functions. Hazards, their associated causal factors, hazard mishap risk, level of risk, and system safety requirements to mitigate hazards can be analyzed during the preliminary design phase of system development [6]. Fig.2 shows an overview of the basic PHA process and summarizes the important relationships. The PHA process consists of utilizing both system knowledge and preliminary hazards to identify system hazards and to find risk factors that are relevant to design safety.

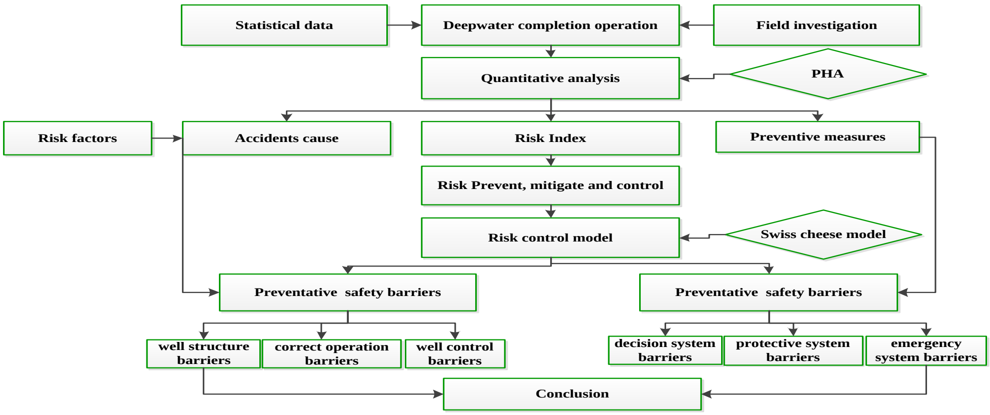

Fig. 1: An integrated risk analysis mode

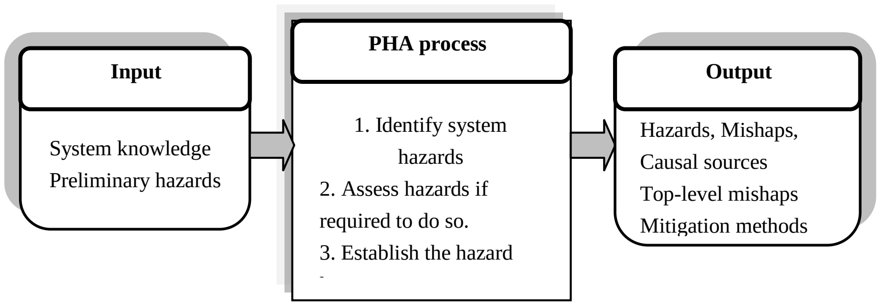

Fig. 2: PHA workflow

Table. 3: RISK index

Severity	Probability
I. Catastrophic	A. Frequent
II. Critical	B. Probable
III. Marginal	C. Occasional
IV. Negligible	D. Remote
	E. Improbable

This column provides a qualitative measure for the potential effect of the identified hazards. Level of risk is calculated based on a combination of mishap severity and probability, and the recommended values are shown in table 3.

5. RCM

Safety barrier is one of the most important concepts and safeguards in maintaining an acceptable level of system safety in oil and gas well risk analysis [7]. Safety barriers, also called safety defences, are physical and/or nonphysical means planned to prevent, control, or mitigate undesirable events or accidents [8]. The degraded of any one or a combination of barriers can cause an accident. An analysis of the Deepwater Horizon accident shows that 8 barriers including well integrity failing, hydrocarbons entering the well undetected and well control lost, hydrocarbons ignited and BOP failure had become degraded and broken. Therefore, it is vital that safety barriers of completion operation should be established to mitigate risks and reliability and validity of safety barriers should be ensured.

Swiss cheese model, a methodology proposed by Dr James T. Reason, are considered as basis of RCM in this article. It explicitly made the analogy from a bank of swiss cheese slices to a set of barriers to prevent an incident or accident with the holes representing potential failures. Failure of one of the barriers may not be sufficient to cause an accident. However a series of failures occur across a number of barriers, there will be an incident to occur [9].

In deepwater well completion, safety barriers will be referred as "envelope of one or several dependent barrier elements preventing fluids or gases from flowing unintentionally from the formation, into another formation or to surface" [10]. The proposed model is intended to build safety barriers, identify vulnerabilities in their safety barrier systems and thereby to mitigate operational risks and to prevent a catastrophic risk, such as giving rise to a blowout which the unintentional fluid flow is from well reservoir to the environment.

6. A Case Study

A list of the main risks including well kick, blowout, lost circulation/mud loss, leakage, sanding, oil-line plugging and other accidents, may be occur in deepwater completion operations. In this section, the deepwater completion blowout accident is analyzed by the proposed model. The model shows why the accident could have happened and how the accident could have been prevented or mitigated, if relevant barriers were kept active.

6.1. Quantitative analysis

In the proposed model, the severity of the blowout accident is evaluated by PHA method first, armed with analysis of possible causes of this accident and corresponding preventive measures. Discussion in the processes where details of the accident may occur and the likely consequences of the different event sequences is also presented in PHA analysis.

The risk index associated with a non-desirable event is defined as:

$$R=P*C \tag{1}$$

Where: R=risk index; P=the probability of the event occurrence (number of events/unit time); and C=the consequence of the event (measure of consequence/event).This value of blowout is calculated by formula (1) and form table 3 on basis of the investigated research data and empirical values.

According to qualitative risk matrix, safety grade can be evaluated. The risk analysis of blowout is presented in the table 4. The results have shown that severity is I. Catastrophic and Probability is C. Occasional.

Table. 4: PHA analysis

Hazards	Mode	Cause	Effects	Risk Index	Preventive measures
Blowout	Drilling oil and gas layer Cementing Perforating Gravel packing Oil and gas testing Installing wellhead	1. The first, second packer invalidation 2. Fluid column pressure of drilling fluid is below the strata pore pressure 3. Drilling suction 4. Tubing or string loss 5. Safety valve, SCSSV failure or unavailable 6. Back pressure valve failure 7. Cement, casing shoe failure 8. Close the BOP failure	Fire Significant casualties Damage of equipment Environmental pollution	I.C	1. Design the reasonable drilling fluid density 2. Design the reasonable body structure of the well 3. Monitor annulus pressure effectively 4. Pull out tools at a predetermined fixed speed 5. Conduct the regular shut-in test 6. Ensure the key equipments effectiveness and reliability

6.2. Risk control model

The control model to prevent blowout accident during deepwater accident is built in accordance with the above risk factors and cause of PHA. Safety barriers is further qualified by focusing the assessment on the completion consequence, such as the drilling oil and gas layer, cementing, perforating and oil and gas testing where blowout is apt to happen. Based on experience from a literature survey and safety barrier function, safety barriers can be divided into preventative and protective safety barriers in control model. Risk control model in deepwater completion is shown in Figure 3. Preventive safety barriers include well structure barriers, correct operation barriers and well control barriers and protective safety barriers consist of decision barriers, protective system barriers and emergency rescue system barriers.

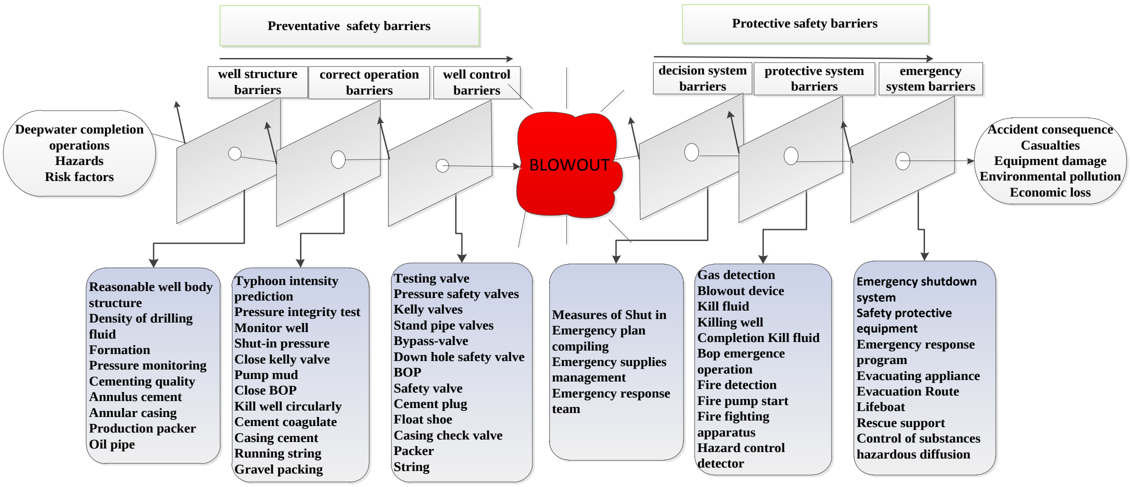

Fig. 3: Deepwater completion risk control model

Reasonable well body structure and the density of drilling fluid etc. are considered as well structure barriers, called first safety barriers. For example, if hydrostatic pressure is lower than formation pressure because of a low density of drilling fluid, blowout may occur. Therefore, drilling fluid is an important barrier in the process of completion. Correct operations, called second barriers, are to monitor annulus pressure timely and fallow the correct operation methods and procedures, etc. Some faulty operations degrade the status of safety barriers. Well control barriers, third barriers involving BOP, safety valve and packer etc. are important safety barriers in the process of completion. Some barriers, such as BOP and a packer, which can be impacted by different operating process and other factors, fail to prevent blowout. If blowout accident has happened, the protective safety barriers can be adopted to control it. Rescue system barriers will play a role to stop development of events and reduce casualty, loss of property.

7. Conclusion

This article has proposed an integrated risk analysis model for deepwater completion operation, based on PHA and the Swiss cheese model. Identification of risk and risk factors in the proposed model is based on statistical data, accident reports and field investigation. Hazards identification, risk cause and safety degree evaluation are evaluated by PHA. Risk control model and safety barriers establishment, including preventative and protective safety barriers to guarantee operation safety are presented by this proposed model. The case study shows that six safety barriers to mitigate or control deepwater completion blowout are established, and fit well with proposed model. Quantitative analysis and risk control model establishment are of major significance to enhance the operation safety.

The project has enabled the operator to make a more informed decision with the various solutions available for undertaking the deepwater completion operation. The proposed model has become a significant tool to prevent the loss caused by the catastrophic and give suggestions to further safety improvement efforts.

8. Acknowledgment

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