Well Integrity Analysis and Application Based on FTA Method

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Abstract

With the increase of development the well integcrity problem are becoming more and more serious. This article uses the Fault Tree Analysis (FTA) method for many factors, such as completion, production and operation process, pressure annulus, the cementing quality, the wellhead system and leakage of pipe string. Many wellbore risk factors to conduct a comprehensive analysis and evaluation. Through the qualitative analysis of wellbore integrity failure risk, determining the level of risk factors and establishing the damage analysis model of the wellbore. According to the selected blocks in Shengli Oilfield example analysis of single wells find out the minimum cut sets, the minimum path sets and structure importance. The results showed that the selected block probability of top event is calculated and it's 0.9961, and the actual selection conforms to statistics prove that the proposed based on the FTA wellbore damage risk analysis method is feasible, and through quantitative analysis and calculation of basic events of different important degree of parameters.

According to these risk factors for prevention of failure risk control measures are put forward, which provides reference for predict wellbore integrity to ensure the safety of oil and gas production run smoothly.

Keywords

well Integrity, FTA analysis, risk evaluation, preventive measures, application example

1. Introduction

Wellbore is the fluid passage inside the well and it is an important part of well control. Any point in the process of drilling and completion and production which fluid flow through maybe the place where fluid leak. It is always the most important problem in oil and gas field exploration and development to prevent the loss of control flow of formation fluid in oil and gas wells. Once the loss of control of formation fluid that especially the wellbore damage caused may lead to serious consequences. In the past years of oil field development, the number of fault wells increased year by year and the well integrity had been destroyed, which influenced the oil field development effect.

2. Risk Assessment Model Establishment of Wellbore Integrity

2.1 Principle of FTA Method

Accident Tree Analysis (ATA) which originated from Fault Tree Analysis (FTA) is one of important analysis methods of safety system engineering, and it can identify and evaluate the risk of various systems. Accident tree analysis whose causality is intuitive, thinking is clear and logic is strong, can not only be used for qualitative analysis, but also quantitative analysis. This method which contains a set of analysis methods and evaluation process and combines qualitative and quantitative calculation model, reflects the systematicness, accuracy and predictability of safety system engineering in the research of safety problems. The original definition of the fault tree is as follows: from the beginning of a possible top event, search for the direct cause event and indirect cause event which causes the top event layer by layer from top to bottom until the basic cause event, and the logical relations between these events are expressed by using a logic diagram.

2.2 Case Model Application

A reservoir in the southwestern structure part is a kind of abnormally high pressure and low permeability lithologic reservoir whose rock formation is tight, so the problem of wellbore integrity is more serious than other areas.

In order to verify the rationality of the structure based on the FTA method, the relevant data such as drilling and completion data, oil production test and production test data and the block productivity construction data is collected. In the process of analysis and description of wellbore risk damage, the damage form of wellbore integrity can be determined as "production casing damage, tubing damage", and combined with the characteristics of single well in this block, this kind of risk is described as "casings of the oil and water wells in this area are badly damaged, the condition of the well is deteriorating, and this leads to the secondary imperfection of well pattern. The problem wells are 60.3% of the total number of wells in this block according to statistics". So the FTA method is used to evaluate and calculate an example.

In order to clarify the relationship between the risk of wellbore integrity, using risk damage of wellbore as the top event, this time 11 intermediate events and 28 basic events are found out, such as Xi (i=1,2 ,…, 28). Based on the fuzzy logic relation that basic events and intermediate events leads to top events, the fault model of wellbore integrity is established, as illustrated in Figure 1. As long as there is a small number of basic events, top events is likely to occur, and this shows the possibility of existence of wellbore risk is great.
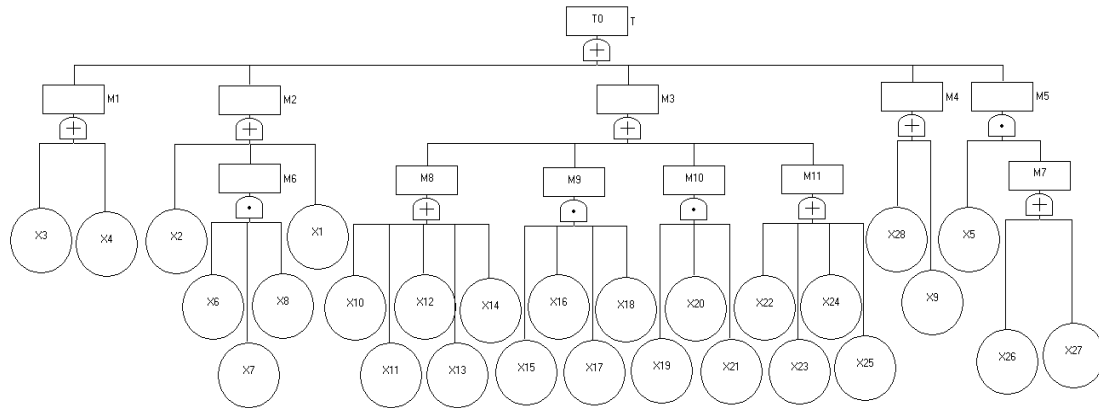
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Figure 1. The Establishment of Analysis Model of FTA Logical Tree

Table 1. The Symbol and Meaning of Risk Factors of FTA Analysis System

Symbol	Representative meaning	Symbol	Representative meaning	Symbol	Representative meaning	Symbol	Representative meaning
T0	Risk damage of wellbore	M10	Tubing damage	X9	Annulus bulging effect	X19	Too high of lifting tonnage
M1	Wellhead system failure	M11	Packer failure	X10	Formation creep collapse casing	X20	Improper pressure control
M2	Poor cementing quality	X1	Uncentralized casing	X11	Casing tieback damage	X21	Hydrogen embrittlement by corrosive fluid
M3	Pipe string leakage	X2	Not in place of cement return	X12	Casing damage caused by sand production	X22	Packing element damage when run in wellbore
M4	Annulus with pressure	X3	Improper of wellhead material	X13	Corrosion caused by oil field water	X23	Improper of design and selection
M5	incompatibility of pipe string	X4	Bad wellhead seal	X14	Hydraulic barrier of annular retention fluid	X24	Improper operation and control
M6	Defects of cement sheath	X5	Large difference of pipe string design	X15	Unreasonable of strength design	X25	Failure of sealing material
M7	Casing head movement	X6	CO_2 damage to the cement sheath	X16	Too high of operating pressure	X26	Reservoir compaction effect

M8	Production casing damage	X7	Gas channeling	X17	Too high of operating temperature	X27	Surface subsidence
M9	Damage of down hole tools	X8	Low displacement efficiency	X18	Failure of corrosion resistance	X28	Thermal expansion effect of annulus

The probability of top events is product of the probability of basic events, so before calculating the risk probability of integrity, every probability of basic events should be first calculated. The probability of basic events should be got by a large number of tests, but can not be achieved in the actual field work, so it is replaced by the frequency approximately.

$$Pi = {Wi} \Big/ {\sum_{i=1}^{n} W_i} \tag{1}$$

In the formula: Pi is the probability of the basic event occurrence, Wi is the basic event, I is the number of well.

The analysis system is calculated by using the Boolean algebra simplification method, which Boolean algebra is a kind of structure function and the method of simplifying is using Boolean algebra principle repeatedly, and the simplifying procedure is: 1. If the algebraic formula includes brackets, they should be removed firstly for functional expansion, 2. Using idempotent law, put similar items together, 3. Making full use of absorption law, simplify directly.

Firstly, analyze the every possible damage risk of wellbore, then determine the probability of each damage risk, lastly the result of probability analysis according to statistics and calculations is made into "probability table of wellbore damage risk", the probability of each event occurrence is shown in Table 2.

Table 2. Calculation Results of Basic Event Probability of Wellbore Damage Risk

Basic event	$X1$	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
probability	0.52	0.02	0.01	0.05	0.002	0.5	0.6	0.8	0.041	0.3
Basic event	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	X_{19}	X_{20}
probability	0.01	0.6	0.58	0.02	0.05	0.03	0.03	0.04	0.01	0.001
Basic event	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	X_{26}	X_{27}	X_{28}		
probability	0.045	0.021	0.0016	0.0003	0.062	0.006	0.0081	0.037		

3. Calculation Analysis of System Application

3.1 Analysis of Cut Sets and Path Sets

A set of basic events that cause top events is called the cut set that is generally more than one in system, and in these cut sets, the cut set that do not contain any other cut sets is called the minimum cut set. The minimum cut set plays an important role in FTA method, which is the essential reason of the top event occurrence and indicate the set of occurrence causes of top events. So the more the minimum cut set, the greater the risk of system. The number of minimum cut sets of this system is 40, as shown in Table 3.

Table 3. The Statistical Table for Calculation of the Minimum Cut Set of System Analysis

No.	minimum cut sets	No.	minimum cut sets	No.	minimum cut sets	No.	minimum cut sets	No.	minimum cut sets
1	X3	9	X15X16X17X18	17	X12	25	X26X5	33	X23
2	X6X7X8	10	X19X20X21	18	X13	26	X4	34	X24
3	X10	11	X22	19	X14	27	X2	35	X25
4	X28	12	X9	20	X27X5	28	X1	36	X11
5	X26X5	13	X23	21	X3	29	X15X16X17X18	37	X12
6	X4	14	X24	22	X6X7X8	30	X19X20X21	38	X13
7	X2	15	X25	23	X10	31	X22	39	X14
8	X1	16	X11	24	X28	32	X9	40	X27X5

In the FTA method, a set of basic events that can not cause top events is called the path set. A set of minimal basic events that can not cause top events is called the minimal path set. Firstly, transform it to a dual system, then get the minimum cut sets of new system that is the minimum path set of original system.

The number of minimum path sets of this system is 72, represented as K72.

$K1= \{X_3 X_6 X_{10} X_{28} X_{26} X_4 X_2 X_1 X_{15} X_{19} X_{22} X_9 X_{23} X_{24} X_{25} X_{11} X_{12} X_{13} X_{14} X_{27}\}, \ldots$

$K3= \{X_3 X_6 X_{10} X_{28} X_{26} X_4 X_2 X_1 X_{16} X_{19} X_{22} X_9 X_{11} X_{12} X_{13} X_{14} X_{27} X_{23} X_{24} X_{25}\}, \ldots$

$K50= \{X_3 X_7 X_{10} X_{28} X_5 X_4 X_2 X_1 X_{18} X_{20} X_{22} X_9 X_{11} X_{12} X_{13} X_{14} X_{23} X_{24} X_{25}\}, \ldots$

$K52= \{X_3 X_8 X_{10} X_{28} X_5 X_4 X_2 X_1 X_{18} X_{21} X_{22} X_9 X_{11} X_{12} X_{13} X_{14} X_{23} X_{24} X_{25}\}, \ldots$

$K72= \{X_3 X_8 X_{10} X_{28} X_{26} X_4 X_2 X_1 X_{15} X_{19} X_{22} X_9 X_{23} X_{24} X_{25} X_{11} X_{12} X_{13} X_{14} X_{27}\}.$

3.2 Fuzzy Logic Relation Analysis

In the analysis of wellbore integrity, every basic event and intermediate event respectively meet the fuzzy or gate logic relation. Namely, suppose last event is A and next event is $B_1, B_2, \ldots B_n$, if any of B occurs, A may occur, then A and $B_1, B_2, \ldots, B_n$ satisfies the fuzzy domain gate logic relation.

$$A=B_1(u) \cup B_2(u) \cup \ldots \cup B_n(u) \qquad (2)$$

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3.3 Importance Analysis and Calculation

The important degree of each basic event is analyzed and calculated from the logical structure of FTA analysis method, and the calculation formula is as follows:

$$I\phi(i) = \frac{1}{2^{n-1}} \sum [\phi(1, xi) - \phi(0, xi)] \tag{3}$$

In the formula, $I_\phi(i)$ is the structure importance of the basic event, $\phi(1, xi)$ is the state of the top event when the state of the basic event status is 1, $\phi(0, xi)$ is the state of the top event when the state of the basic event status is 0, n is the number of basic events.

Using the nature that the probability function of top events is a multiple linear function, the probability importance of basic events that is influence degree of the occurrence probability of basic events on the occurrence probability of top events, can be obtained by solving first partial derivative of variables, and the calculation formula is as follows:

$$I_Q(i) = \frac{\partial Q}{\partial q_i} \tag{4}$$

In the formula, $I_Q(i)$ is the probability importance of the basic event, Q is the probability of top events, q_i is the probability of the basic event.

Table 4. Calculation Results of the Parameters Importance of the Wellbore Damage Risk

Basic event	Uncentralized casing（X1）	Not in place of cement return （X2）	Formation creep collapse casing （X10）	Casing damage caused by sand production（X12）	Corrosion caused by oil field water （X13）	Failure of sealing material（X25）	Annulus bulging effect （X9）
structure importance	0.05	0.05	0.05	0.05	0.05	0.05	0.05
probability importance	0.9	0.9	0.9	0.9	0.9	0.9	0.9
risk importance coefficient	0.3043	0.034	0.1014	0.2029	0.2705	0.0209	0.0139
Basic event	Bad wellhead seal（X4）	Thermal expansion effect of annulus（X28）	Packing element damage when run in wellbore （X22）	Hydraulic barrier of annular retention fluid（X14）	CO_2 damage to the cement sheath（X6）	Gas channeling （X7）	Low displacement efficiency（X8）
structure	0.05	0.05	0.05	0.05	0.0167	0.0167	0.0167

importance probability	0.9	0.9	0.9	0.8	0.018	0.016	0.72
importance risk importance coefficient	0.0135	0.0125	0.0071	0.0068	0.0049	0.0049	0.0049
Basic event	Improper of wellhead material（X3）	Casing tieback damage（X11）	Improper of design and selection（X23）	Improper operation and control（X24）	Large difference of pipe string design（X5）	Failure of corrosion resistance （X18）	Unreasonable of strength design（X15）
structure importance	0.05	0.05	0.05	0.05	0.05	0.0125	0.0125
probability importance	0.6	0.6	0.5	0.5	0.0141	0.000045	0.000036
risk importance coefficient	0.0034	0.0034	0.00054	0.0001	0.000009	0.0000061	0.00000061
Basic event	Too high of operating pressure（X16）	Too high of operating temperature （X17）	Surface subsidence （X27）	Surface subsidence （X26）	Surface subsidence （X19）	Improper pressure control（X20）	Hydrogen embrittlement by corrosive fluid（X21）
structure importance	0.0125	0.0125	0.025	0.025	0.0167	0.0167	0.0167
probability importance	0.00006	0.00006	0.0002	0.0002	0.000045	0.00045	0.00045
risk importance coefficient	0.00000061	0.0000006	0.0000005	0.00000041	0.00000015	0.00000015	0.00000015

Table 5. Classification of Calculation Results of Basic Events Importance

Classification	Risk rank	Description
IV	High	Three importance parameter values is high, indicating that this kind of basic events has great influence on damage risk of wellbore from both the logical structure and the occurrence probability, and this kind of events should be considered first when the measure of preventing wellbore integrity is drafted.

III	Importance	The probability importance and structure importance is large, and this kind of events should be considered as the secondary risk factor when the measure of preventing wellbore integrity is drafted.
II	Middle	The probability importance is large and the structure importance is the second, this shows that the occurrence probability of this kind of events has a significant impact on top events.
I	Low	Three importance degree are small, this shows the risk effect on top events with changing probability of this kind of events is not obvious, generally as a reference factor.

The order of structure importance of this system is as follows:

I(3)=I(10)=I(28)=I(5)=I(4)=I(2)=I(1)=I(22)=I(9)=I(23)=I(24)=I(25)=I(11)=I(12)=I(13)=I(14)>I(26)=I(27)>I(20)=I(21)=I(7)=I(8)=I(6)=I(19)>I(16)=I(17)=I(18)=I(15)

Risk importance coefficient: measure importance standard of the basic event from both perspective of sensitivity and probability, and the calculation formula is I.

$$C_i = \frac{\partial \ln Q}{\partial \ln q_i} \tag{5}$$

In the formula, C_i is the risk importance coefficient of the basic event, Q is the probability of top events, q_i is the probability of the basic event.

Using the nature that the probability function of top events is a multiple linear function, the probability importance of basic events can be obtained by solving first partial derivative of qi variables, then calculation results of the importance coefficient of each event are got, as shown in Table 4.

According to the results, the order of risk importance coefficient of each basic event is as follows:

Cg(1)>Cg(13)>Cg(12)>Cg(10)>Cg(2)=Cg(2)>Cg(25)>Cg(9)>Cg(4)>Cg(28)>Cg(22)>Cg(14)>Cg(8)=Cg(6)=Cg(7)>Cg(11)=Cg(3)=Cg(3)>Cg(23)>Cg(24)>Cg(5)>Cg(15)=Cg(16)=Cg(17)>Cg(18)>Cg(27)>Cg(26)>Cg(21)=Cg(20)>Cg(19)>Cg(7)=Cg(8)=Cg(6)

Compared with the well number ratio 100% which exist actual damage, the probability calculation result of top event is 0.9961, and the error is only 0.0039 and the relative error is within the allowable range of project. This shows the FTA evaluation model is reasonable, and the risk analysis method of wellbore based on FTA is feasible, so the occurrence probability of high risk importance coefficient of basic events should be strictly controlled in the process of well completion, thereby the risk of oil and gas out of control caused by wellbore damage is reduced.

Through actual analysis, 41% of the total casing damage wells are water injection wells, water injection is the main cause of casing damage. Because of poor water quality or heavy polluted reservoir or high water injection pressure, the casing of water injection well has problems such as casing damage and

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hole shrinkage. Low permeability of formation and development of water sensitive clay layer lead to poor conductivity; unreasonable cement return height or too high injection pressure lead to casing deformation or breakage of water injection wells; the oil well casing damage is near reservoir area, and the frequent fracturing of oil wells, the great buried depth of the reservoir and high ground stress can also cause damage to the casing.

4. Conclusions and Suggestions

By comparing the order of probability importance and risk important coefficient of each event, the most main factors that influence the damage risk of this block include uncentralized casing, corrosion caused by oil field water, casing damage caused by sand production, casing collapse caused by formation creep, unreasonable cement return height and seal material failure.

According to the FTA analysis method, the risk factors should be strengthened to control and events of high probability should be focused on prevention and control in the completion process, specific corresponding measures: centralize the casing as far as possible, improve the uniformity of the thickness of cement sheath, improve the performance of the cement slurry system, require smooth of the well trajectory, improve the collapsing strength of casing, well completion with thick wall casing of high strength in oil layer section, increase thickness and steel grade of casing, improve cementing quality, increase cement return height. In addition, attention should be paid to the water injection well to improve the water quality and enhance strength and corrosion resistance of casing, and at the same time, the cement is required to return to the ground.

Because of the different reservoir conditions leading to the change of block conditions and major technology and down hole tools, the analysis conclusion is not immutable. Wellbore integrity failure is the combined action of a variety of basic events, therefore "one well corresponded with one strategy" need to be worked out according to the system analysis, the probability calculation of risk factor of "last events" or "intermediate events" should be analyzed targeted, and the main factors of wellbore risk damage should be clearly studied, these can give better suggestion for control measures of wellbore integrity of similar wells or blocks.

Acknowledgement

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