

Risk analysis of subsea x-mas tree leakage

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ABSTRACT

Crude oil leakage is the most serious type of accidents in offshore petroleum industry, which have led to eco-catastrophe and huge economic loss. Subsea X-mas tree, as the first equipment in the subsea production chain, always takes a high risk of leakage. In order to analyze the risk of leakage, this paper is devoted to analysis of oil leakage based on fault tree analysis. Through the construction of leakage fault tree, qualitative analysis is conducted, obtaining minimal cut sets and basic event importance. The crucial basic events failure possibility for 3, 5, 10 year is calculated, and the 2nd order minimal cut sets failure possibility and dominating top events probability for 3, 5, 10 years in different conditions of X2, X4, X10 are computed by Boolean algebra. The quantitative analysis result shows that improving X2 and X10, especially when the X2 failure rate in 0.5λ and X10 failure rate in 0.25λ can reduce the risk of failure.

KEY WORDS: Subsea tree; Leakage; Fault tree analysis; Failure rate; Failure mode and effects analysis;

1. INTRODUCTION

In recent years, with the continuous development of technology, the demand of oil and gas is more and more huge. Due to the onshore oil and gas resources increasingly depleted, many countries put their eyes to the ocean. Subsea production system (SPS) with its significant technical advantage and considerable economic benefit has attractive to some company (Wang 2009). SPS is a vital way of oil and gas production in offshore engineering, ranging from 20m to 3,000m. They are more complex in structure, including several wells, manifolds, X-mas trees (XT), pipelines, risers, PLETs, and processing/commingling facilities etc. Subsea system, shown in Fig.1, is a mixture of a great many facilities. In the beginning, crude oil or gas is explored from wells. Furthermore, it flows through XT, Jumper, Manifold, PLET and PLEM etc. Finally, it is transferred to a fixed or floating facility, or directly to an onshore installation. The subsea XT, also named Christmas tree, is one of the key equipment of SPS explicitly

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denoted in Fig. 3 played an important role in the subsea production process (Hu 2013) .

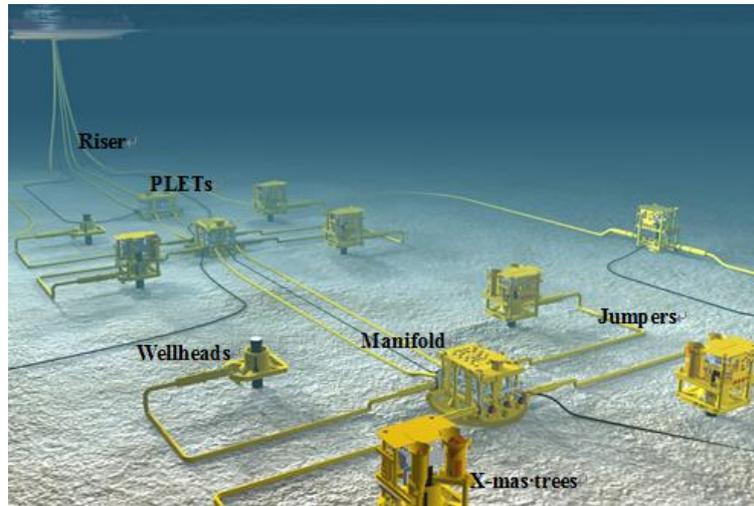


Fig. 1 Subsea production system

As the subsea industry moves into deeper waters, technical challenges and associated risks increase with significantly amplified failure costs. The environment of subsea XT is same with other equipment of SPS always very harsh: low temperature, high pressure, difficulties of maintenance and repair, large spreading ranges of subsea layout. Meanwhile, as the first equipment which crude oil flow through after being exploited from well, subsea XT takes an even higher risk of leakage than other equipment in SPS. It always bears highest pressure, highest temperature, strongest erosion and severest corrosion from oil in the entire SPS. Crude oil leakage is the most serious type of accidents in offshore petroleum industry, which have led to many ecocatastrophes and huge economic loss. In addition, the cost for XT in both production and installation is very high (Mamman 2009). Therefore, leakage risk in XT absolutely exists and definitely ranks high, and the risk analysis concerning leakage in subsea XT tree is essential. Although the sealing techniques used in XT are mature and all sealing components pass all the tests before assembling, sealing failure ranks highest in the risk of leakage in XT. Many methods, such as Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), Event Tree Analysis (ETA) and so on, have been developed and used in system risk analysis. Each method has its advantages and disadvantages (Zhou 2009,Langseth 2007, Kim 2013,Chen 2012,Roberts 2009,Faber 2012, Ren 2008, Kim 2011,Limin 2003,Li 2012). Additionally, the concept of a FTA is heavily utilized in the aerospace, automotive, and electronics industries. Especially in the aerospace industry, FTA is a common reliability engineering tool. One example is the area of troubleshooting. In case of a system malfunction on a mission, quick and precise identification of cause is a necessity for the success of the mission and the safety. Xianwei Hu had figured out the failure probability and found out the sensitive basic events of the leakage of SPS by fuzzy FTA. Fault trees (FT) can be used in the same fashion in the hydrospace industry where a quick and remote first diagnostic determines the magnitude of corrective actions and interventions. FTAs determine

minimal cut-sets which allow the identification of critical functions or components and which identify common cause potentials (Frank 2001). Mamman(2009) applied FMECA to Christmas tree and made the protection strategy to improve the reliability of valves. However, few researches on the application of FTA in the leakage analysis of subsea XT are reported.

The paper is organized as follows. First, analyze the XT structure, seal, process, and build up the leakage fault tree, calculate the tree's minimal cut sets and basic event importance. Second, according to the result of qualitative fault tree analysis and failure rate theory, the Offshore Reliability Data (OREDA) (OREDA Participants 2009) and Boolean algebra, quantitative analysis is made. Then we can apply FMEA to further analysis. The causes we got from the FMEA can be used to ensure the correct basic events.

2. FTA OF XT LEAKAGE

The subsea XT consists of wellhead connector, isolation sleeve, tubing hanger, up crown plug, down crown plug, inner tree cap, debris cap, tree body and valve plugs. In the normal production, crude oil is exploited from well through wellhead connector and surface controlled sub-surface safety valve (SCSSV) into the XT. Crude oil passes the production master valve (PMV) and production wing valve (PWV), then going to the tree-jumper connector. In this process, all the seal equipment is working to protect XT from leaking. All the sealing points and components are denoted in Fig. 2, except the few points which can't be seen in the figure.

FTA is a deductive method to identify the causal relationships leading to a specific system failure mode, which can be expressed in terms of combinations of component failure modes and operator actions. So, how to conduct fault tree analysis? Firstly, the top undesired event, namely top event, is identified. Additionally, direct causes of top event, namely middle event, are identified. And through a certain steps of deductions, the initial causes, namely basic events, are identified. Finally, fault tree is completed by a combination of events and logic gates. FTA is particularly useful for highly complex systems or processes in which the outcome of one or more non-critical, lower-level events may produce an undesired critical event.

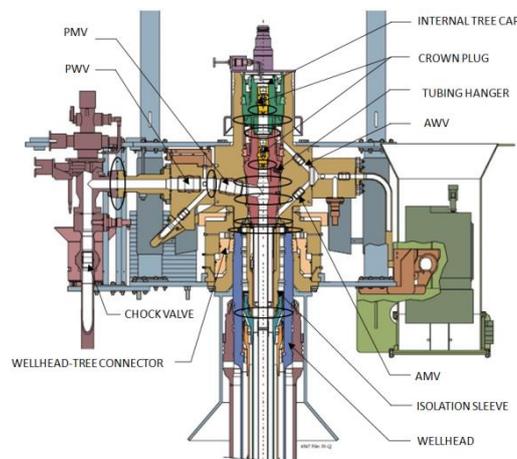


Fig. 2 Typical XT with denoted structure and sealing points

2.1 Fault Tree Construction

The subsea XT mainly consists of the mechanical system and the control system. The control system is an electro-hydraulic control system, in which electronic control module and hydraulic control module work together to control the opening or closing of the valves in subsea XT. And the failure modes of control system are complex and beyond the research target of this work, so control system failure is treated as one basic event here. It was discovered that internal leakage consequence which may be erosion or the effect is not extremely serious in a short period of time when XT is still under control, but the probability is high. However, if XT loses control, the result is opposite.

The paper considers two conditions of leakage external leakage and internal leakage, to build up the XT leakage fault tree. We choose XT leakage as the top event. As the over design of mechanical components in XT, other causes which might lead to leakage, like rupture and defect, are extremely rare, because of mechanical components themselves are not easy to fail. Therefore, this work ignores the effects of other causes accordingly for simplify and focus on sealing failure and valves failure which have caused the overwhelming majority of leakage risks in XT. Fault tree of leakage of XT is built up through deduction, shown in Fig. 3. In addition, events, including top event, middle events and basic events, are listed in Table 1.

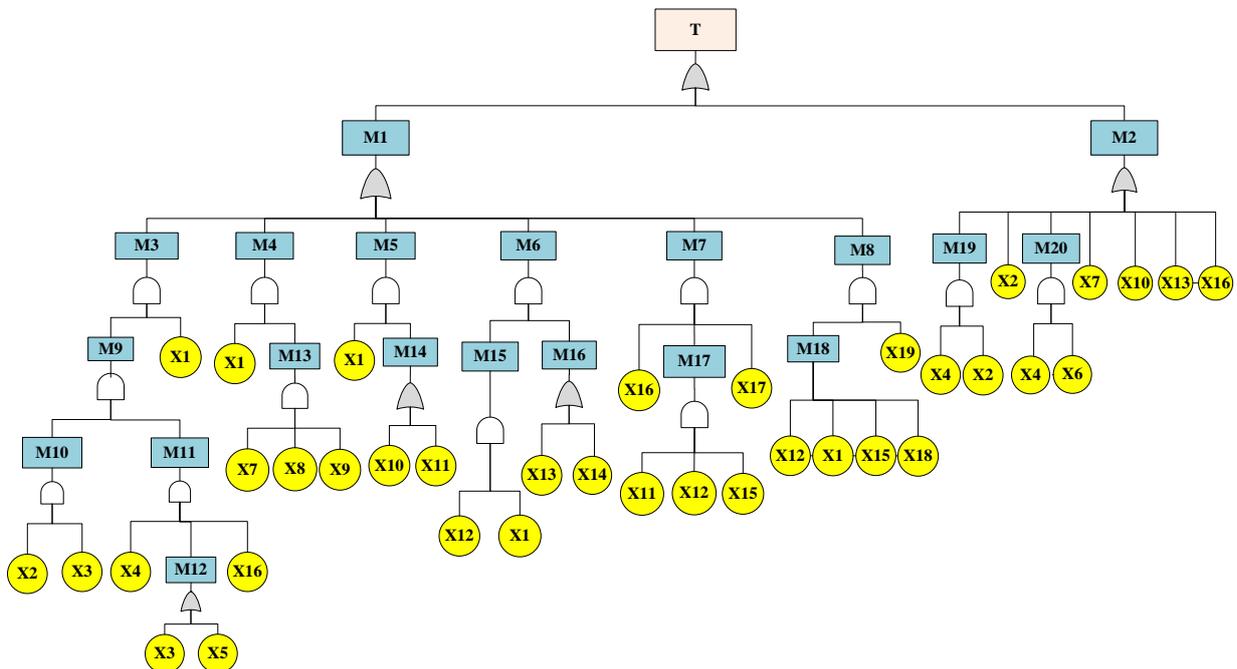


Fig. 3 Fault tree of leakage of XT

Table 1.Events list of fault tree

NO.	Events	NO.	Events
T	Leakage in subsea X-tree	M20	Leaking between crown plug and tree cap
M1	External leakage(ELP)	X1	Fail to close SCSSV on demand
M2	Internal leakage(ILP)	X2	Fail to seal Tubing hanger isolation plug (above bore protector)
M3	Leakage in tree cap	X3	Fail to seal between tree body and tree cap
M4	Leakage in wellhead –tree	X4	Fail to seal between tree cap and tubing hanger
M5	Leaking between PMV and PWV (including PMV)	X5	Fail to seal up crown plug
M6	Leaking between PWV and choke valve (include PWV)	X6	Fail to seal down crown plug
M7	Leakage in choke and flowline (include choke valve)	X7	Fail to seal tubing hanger body (blow bore protector)
M8	Leakage in tree-jumper connector	X8	Fail to seal between isolation sleeve and tree body
M9	leaking between inner tree cup crown plug and tree body	X9	Fail to seal wellhead connector
M10	leaking between tree cap and tree body	X10	PMV seal failure
M11	leaking between crown plug and tree cap	X11	Fail to seal between PMV plug and PWV plug
M12	Fail to seal among crown plug tree body and tree cap	X12	Fail to close PMV through mechanical mechanism
M13	Leakage in wellhead –tree connector	X13	PWV seal failure
M14	Fail to seal between PMV and PWV	X14	Fail to seal between PWV plug and choke valve plug
M15	Fail to close SCSSV and PMV on demand	X15	Fail to close PWV through mechanical mechanism
M16	Fail to seal between PWV and choke valve	X16	Choke valve seal failure
M17	Fail to close SCSSV PMV PWV on demand	X17	Fail to seal between choke valve and pipe
M18	Fail to close SCSSV PMV PWV and choke valve on demand	X18	Fail to close choke valve through mechanical mechanism
M19	Leaking between tree cap and tubing hanger	X19	Failure of tree-jumper connector

2.2 Qualitative Fault Tree Analysis

The purpose of qualitative fault tree analysis is to work out minimal cut sets and cut-sets importance of each basic event being of great value to help us get an overall view of leakage of XT, which is the key step to identify the accident models, reasons and effects.

By Boolean algebraic operation (Kececioglu 1991, Purba 2014), top event can be abbreviated into standard expression shown in Eq.1. Then we can easily get the minimal cut sets. As we all know the less basic event of minimal cut set is, the higher of its occurrence frequency will be. Accordingly, X2, X7, X16, X13, X10 are the higher occurrence frequency events.

$$\begin{aligned}
 T = & X1X2X3X4X6 + X1X2X3X4X5X6 + X1X7X8X9 + X1X10 \\
 & + X1X11 + X1X12X13 + X1X12X14 + X1X12X15X16X17 \\
 & + X1X12X15X18X19 + X2X4 + X4X6 + X2 + X7 + X16 \\
 & + X13 + X10
 \end{aligned} \tag{1}$$

$$\begin{aligned}
 & \{X1, X2, X3, X4, X6\}, \{X1, X2, X3, X4, X5, X6\}, \{X1, X12, X14\}, \\
 & \{X1, X7, X8, X9\}, \{X1, X10\}, \{X1, X11\}, \{X1, X12, X13\}, \\
 & \{X1, X12, X15, X16, X17\}, \{X1, X12, X15, X18, X19\}, \\
 & \{X2, X4\}, \{X4, X6\}, \{X2\}, \{X7\}, \{X16\}, \{X13\}, \{X10\}
 \end{aligned} \tag{2}$$

Every basic event importance can be figured out through Eq3. Where k is the total events, Er is represent minimal cut sets, r changes from 1 to k, mr is the number of basic event in the minimal cut sets which contains Xi. The result is showed in Eq3 (Zhang 2002).

$$I_k(i) = \frac{1}{k} \sum_{r=1}^k \frac{1}{m_r(X_i \in E_r)} \quad (i = 1, 2, 3...n) \tag{3}$$

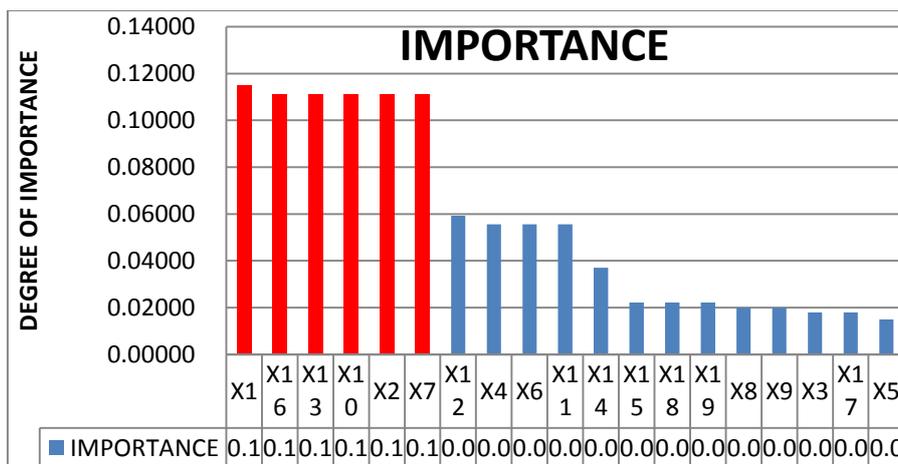


Fig. 4 Basic event importance

Analysis the minimal cut sets results, {X1, X10}, {X2, X4}, {X4, X6}, {X1, X11} are the 2 order minimal cut sets and very important to the top event. According to the basic event importance result showing in the Fig 4, we can get those more important basic events: X1, X16, X13, X10, X2, X7, X12. As we all know, single event in a cut set has the highest important degree and the more often occurrence of the basic event, the higher important degree. So, X1, X2, X4, X6, X7, X10, X13, X16 would be considered in advance in the aspect of quantitative FTA.

2.3 Quantitative Fault Tree Analysis

The failure rate function expresses how likely it is that an item that has survived up to time t , will fail during the next unit of time. To give the mathematical definition of the failure rate function, we start with the time to failure, T . It is generally impossible to predict the exact value of the time to failure, and T will therefore be a random variable with an associated distribution. The failure rate function may be defined mathematically as:

$$z(t) = \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} P(t < T \leq t + \Delta t | T > t) \quad (4)$$

This implies the approximation:

$$z(t) \cdot \Delta t \approx P(t < T \leq t + \Delta t | T > t) \quad (5)$$

The right hand side of this equation denotes “the probability that the item will fail in the time interval $(t, t + \Delta t)$, when the item is still functioning at time t . The main part of the failure events in the OREDA database will therefore come from the useful life phase, where the failure rate is close to constant. All the failure rate estimates presented in this handbook are therefore based on the assumption that the failure rate function is constant and independent of time, in which case $z(t) = \lambda$ (6). The failure rates are assumed to be exponential distributed with parameter λ . Using this, different life failure probability could be calculated as equation: $P = \lambda \Delta t$ (7).

Table 2. Failure rate and probability of crucial events

Events	Failure rate (per10 ⁶ hours)	Failure probability (For 3 years)	Failure probability (For 5 years)	Failure probability (For 10 years)
X1	0.44	0.0115632	0.019272	0.038544
X2	0.69	0.0181332	0.030222	0.060444
X4	1.16	0.0304848	0.050808	0.101616
X6	1.16	0.0304848	0.050808	0.101616
X7	0.63	0.0165564	0.027594	0.055188
X10	0.59	0.0155052	0.025842	0.051684
X13	0.59	0.0155052	0.025842	0.051684
X16	0.06	0.0015768	0.002628	0.005256

Table 3 Probability of 2nd order minimal cut sets

2 nd order minimal cut sets	Failure probability (For 3 years)	Failure probability (For 5 years)	Failure probability (For 10 years)
{X1, X10}	1.792897e-4	4.980270e-4	1.992108e-3
{X2, X4}	5.527869e-4	1.535519e-3	6.142077e-3
{X4, X6}	9.293230e-4	2.581452e-3	1.032581e-2

3. RESULTS AND DISCUSSIONS

The first and second order minimal cut sets which are composed of crucial events of top event plays a dominant role in top event. Then, this kind of top event is defined as dominating top event (DTE). The probability original DTE of X1, X2, X4, X6, X7, X10, X16 is calculated in equation 7.

$$DT2 = X1X10 + 0.5X2X4 + X4X6 + 0.5X2 + X7 + X10 + X13 + X16 \quad (8)$$

X2, X4, X10 have the highest importance in the DTE. According to the table 2 and 3, the 0.5λ and 0.25λ of X2, X4, X10 for 3, 5, 10 years are calculated, as well as the corresponding failure probability, shown in the table 4 and 5. If second order cut sets contain the any one of X2, X4, X10, its probability should be recalculated, showing in the table4.

Table 4 0.5λ of partial crucial basic event and minimal cut sets

Partial 1st and 2 nd order minimal cut sets 0.5λ	Failure probability (For 3 years)	Failure probability (For 5 years)	Failure probability (For 10 years)
0.5X2	9.0666000E-03	1.5111000E-02	3.0222000E-02
0.5X10	7.7526000E-03	1.2921000E-02	2.5842000E-02
{0.5X2, X4}	2.7639345E-04	7.6775950E-04	3.0710385E-03
{0.5X4, X6}	4.6466150E-04	1.2907260E-03	5.1629050E-03
{X1, 0.5X10}	8.9644850E-05	2.4901350E-04	9.9605400E-04

Table 5 0.25λ of partial crucial basic event and minimal cut sets

Partial 1st and 2 nd order minimal cut sets 0.25λ	Failure probability (For 3 years)	Failure probability (For 5 years)	Failure probability (For 10 years)
0.25X2	4.5333000E-03	7.5555000E-03	1.5111000E-02
0.25X10	1.3819673E-04	3.8387975E-04	1.5355193E-03
{0.25X2, X4}	1.1616538E-04	3.2268150E-04	1.2907263E-03
{0.25X4, X6}	2.2411213E-05	6.2253375E-05	2.4901350E-04
{X1, 0.25X10}	2.2411213E-05	6.2253375E-05	2.4901350E-04

To investigate the effects of failure rates on the failure probability of the DTE, the probability DTE for 3, 5, 10 years is computed using the equation 7 under the two different conditions that failure rate of X2, X4, X10 are respective 0.5λ or 0.25λ , using the failure rates given in Table 5 and 6. X2 is chosen as the example, as follows, the total data is shown in the Fig 5.

$$DT2 = X1X10 + 0.5X2X4 + X4X6 + 0.5X2 + X7 + X10 + X13 + X16$$

$$DT22 = X1X10 + 0.25X2X4 + X4X6 + 0.25X2 + X7 + X10 + X13 + X16$$

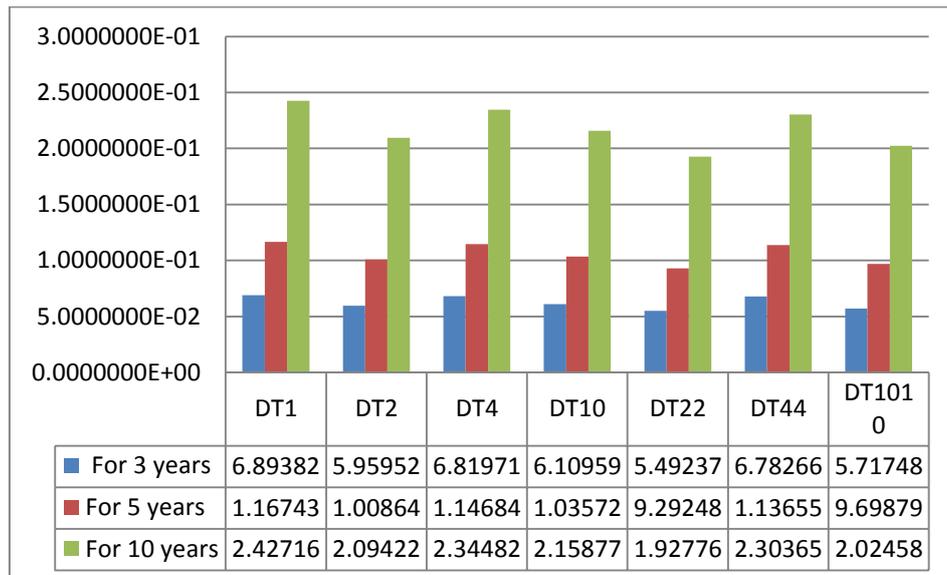


Fig. 5 Failure probability of dominating top events

The results indicate that the failure rate of X2 has a relatively high impact on the probability of the DTE, and that X4 has smallest effects. The difference of X2 in different failure rate value is very close. Comparison the columns in the Fig5 the probability of DTE is big change, when X2 in different value. Therefore, reducing the failure rate of X2 will reduce the probability of the DTE, and chosen 0.5λ is suitable. There is little meaning to reduce the failure rate of X4. X10 has the higher influence on the probability of DTE, when the failure rate is 0.25λ . It can be seen that 10 years has the obviously change extent. It demonstrates that the different failure rate has the highest influence on the 10th year probability of DTE. Reducing the failure rate is helpful to length the system life. X2 represents of fail to seal Tubing hanger isolation plug (above bore protector). The seal is the key technology in subsea production system, especially subsea tree. This position seal uses the mental to mental technology which is the latest. PMV seal failure is represented by X10.

4. FMEA FOR VALVES

X1, X16, X13, X10 are all relative to valves seal, the failing to close the valves, and oil-out seal which may contribute to the top event happen in a large extent. So those

events' reliability is crucial to affect the probability of the leakage fault. Therefore, using FMEA to analyze them is essential.

FMEA is a technique that permits evaluation of facilities to predict critical failure modes and the resultant consequences in order to determine appropriate maintenance tasks for the facilities. To push the process and motivate the brainstorm of the experts who is using FMEA, function, functional failure, failure modes should be figure out. The purposes of FMEA are to obtain the functional failures and initial basic events, which will be used to learn the cause of functional failure.

According to the result of qualitative FTA, we can get the crucial basic events. Those events divide the range of FMEA. We chose valves as the example, due to the worksheet of all crucial events is huge. The result is shown in a table (Table.6), through the process of FMEA. This table lists the cause of crucial basic event which cannot show in the fault tree.

Table.6 FMEA records of valves' functional failure

Function	Functional Failure	Failure Modes	Causes
To control flow of fluid	Complete loss of flow control	SCSSV fail to close on command	Actuation system failure
			Control system failure
			Erosion
			Corrosion
		Installation error	
		PMV fail to close on command	Actuation system failure
			Control system failure
			Erosion
			Corrosion
		Installation error	
		PWV fail to close on command	Actuation system failure
			Control system failure
			Erosion
			Corrosion
		Installation error	
		Choke valve fail to close on command	Actuation system failure
	Control system failure		
	Erosion		
	Corrosion		
	Installation error		
Leakage	PMV seal failure	Corrosion	
		Design fault	
		Installation error	
	PWV seal failure	Corrosion	
		Design fault	
		Installation error	
	Choke valve seal failure	Corrosion	
		Design fault	
		Installation error	

5. CONCLUSIONS

This paper proposes a new method not only make the risk analysis, but also propound the way to find out the most efficient improvement measures. Analysis of oil leakage is successfully completed. Fault tree of XT leakage is built up. The qualitative fault tree analysis was done, and we got the minimal cut sets and every basic event's importance. We got the crucial basic event. They are useful in subsea tree inspection and maintenance.

According to the failure rate functions, the different years failure rate of crucial basic events are computed. Comparison of the probability of DTE for 3, 5, 10 years in different condition of X2, X4, X10, the quantitative analysis obviously shows that it is the efficient way to reduce the risk of failure by improving X2 and X10, especially when the X2 failure rate in 0.5λ and X10 failure rate in 0.25λ .

This paper assessed the failure characteristics of valves based on the result of FTA using FMEA technique. The causes of the loss of flow control are mainly actuation system failure, control system failure, erosion and corrosion. The causes of seal failure contain corrosion, design fault and installation error.

ACKNOWLEDGMENTS

The result of this research is supported by the National Development and Reform Commission, the special project of ocean engineering equipment research and development and industrialization ("subsea tree r&d and industrialization" No. F13QW)

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