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SAFETY IN SUBSEA PETROLEUM PRODUCTION SYSTEMS: SUBSEA CHRISTMAS TREE CASE STUDY

BEZPIECZEŃSTWO W SYSTEMACH DO PODWODNEJ EKSPLOATACJI ZŁÓŻ ROPY NAFTOWEJ NA PRZYKŁADZIE GŁOWICY EKSPLOATACYJNEJ

Abstract

The paper presents an analysis of valves used for closing and opening production tubing, located on the production line. The main safety valves analysed in this work are located in the Christmas Tree and in the Downhole Safety Valve. The analysis was conducted using FMEA; it found that for each basic Christmas Tree's gate valve, the most dangerous failure modes are external leaks and "fail to close" in the open position of the valves. For the Downhole Safety Valve, the most dangerous fault can occur in the open position of the valve. The Downhole Safety Valve and the Christmas Tree complement each other, thus ensuring safety during oil and gas production.

Keywords: *safety in subsea petroleum production systems, Christmas Tree's safety valves*

Streszczenie

W artykule przedstawiono analizę zaworów przewodu wydobywczego, umiejscowionych w głowicy eksploatacyjnej oraz zawór wgłębny bezpieczeństwa. Analizę przeprowadzono metodą FMEA; stwierdzono, że dla każdego podstawowego zaworu zasuwowego głowicy eksploatacyjnej najgroźniejsze są wycieki zewnętrzne, a także uszkodzenie w pozycji otwartej. Podobnie dla zaworu wgłębnego bezpieczeństwa. Zawór wgłębny bezpieczeństwa i podstawowe zawory zasuwowe uzupełniają się nawzajem gwarantując bezpieczeństwo.

Słowa kluczowe: *systemy bezpieczeństwa przy wydobywaniu ropy i gazu, zawory bezpieczeństwa w głowicy eksploatacyjnej*

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1. Introduction

Demand for oil and gas continues to grow, but ground-based hydrocarbon deposits begin to slowly deplete. Therefore, there is expected increase in performed offshore drillings and underwater installations in the coming years. Many wells located in shallow waters are already heavily exploited, so the search for hydrocarbons begins to move into deeper regions of the sea. Today, there are more than 9,000 offshore platforms operating worldwide, serving more than 10,000 wells, and their number will continue to grow [2].

The subsea mining industry puts a strong emphasis on the reliability of equipment. Equipment used in water are typically 5 times more expensive than equipment used for oil and gas extraction on land because all the situations of intervention or repair are associated with high costs. Breakdowns at sea can have additional devastating effects on the environment. An example is the 2010 explosion at the American platform rig Deepwater Horizon in the Gulf of Mexico, which was the cause of the largest oil spill in the world. It is assumed that 780 000 m^3 of oil leaked into the Gulf and the contaminated area consisted of 6,500 to 176,000km^2. Many factors are consisted during safe production of oil and gas from the seabed, but the most important components in the system of subsea production are subsea the Christmas Tree and the Downhole Safety Valve.

2. Christmas Tree

The most important element in the subsea production system is the Christmas Tree (XT). The Christmas Tree is mounted on the wellhead at the seabed. The XT is a set of valves mounted on a specially designed steel block.

Fig. 1. Subsea Christmas Tree [www.gizmodo.com]

The main task of the Christmas Tree is to control the flow of hydrocarbons from the well [5]. Christmas Trees also allow for the injection of various chemicals in order to remove or prevent the formation of hydrocarbon plugs, corrosion, or other prejudicial obstructions having bad influence to the production system. The design of the Christmas Tree also allows for access to the borehole in order to carry out all kinds of maintenance and workovers. The Christmas Tree can also be used for pumping water, gas or other factors to the lode. The Christmas Tree provides additional features, such as pressure and temperature monitoring and flow rate control. The construction of the Christmas Tree may vary depending on the requirements of the project and the area of extraction. The average body weight of a Christmas Tree is from 50 to 70 tonnes. Pressures of exploration for Christmas Trees are standardised and are successively 5,000 psi (35 MPa), 10,000 psi (69 MPa), 15,000 psi (103 MPa) and for ultra-deepwater Christmas Trees: 20,000 psi (138 MPa) [6]. All valves in the Christmas Tree must withstand the same pressure as the Christmas Tree. All equipment is designed to operate at temperatures from 35° to 250°F (2°C to 120°C) [7]. Inside the Christmas Tree, the operating temperature is close to the lode temperature and pressure reservoir decreased by hydrostatic pressure related to the difference between the depth of the lode and the Christmas Tree as well as the linear and local losses. Linear losses derived from friction forces occurring between the elements of the fluid in all its mass and the friction against the walls of the passageway along its length. Take-offs are local obstructions in the flow and changes in the shape of the channel or the velocity of the stream.

Very often, the wells are drilled at depths of 1,500 meters or more. Such depths put high demands on the technical issues; therefore, ultra-deepwater Christmas Trees are used for the exploration of such lodes.

2.1. Safety valves in Christmas Tree

Three valves located in the Christmas Tree were analysed which are important in production of hydrocarbons :

- Production Master Valve (PMV) is the primary and the most important valve in the Christmas Tree. It provides insulation between the borehole and the production tubing, wherein the hydrocarbons flow from the Christmas Tree to the manifold. During the exploitation of the lode, the valve is in the fully open position. The PMV must be strong enough to withstand the pressure prevailing in the well and prevent an uncontrolled leakage of hydrocarbons from the well.
- Production Wing Valve (PWV) is used for closing and opening the XT under normal operating conditions. Just like the Production Master Valve, it is responsible for securing the flow of hydrocarbons from the well.
- Annulus Master Valve (AMV) is the main valve preventing a leak of hydrocarbons from the wellbore to annulus [1].

These valves are fail-safe gate valves. It is a very popular type of valves used in Christmas Trees. This type of valves not only meets the safety function in the event of failure, but also allows for the closure of the valves in the XT without injecting heavy drilling mud into the well in order to eliminate flow from the reservoir into the hole. Closing the valves may be necessary, for example, during pressure and function tests [11].

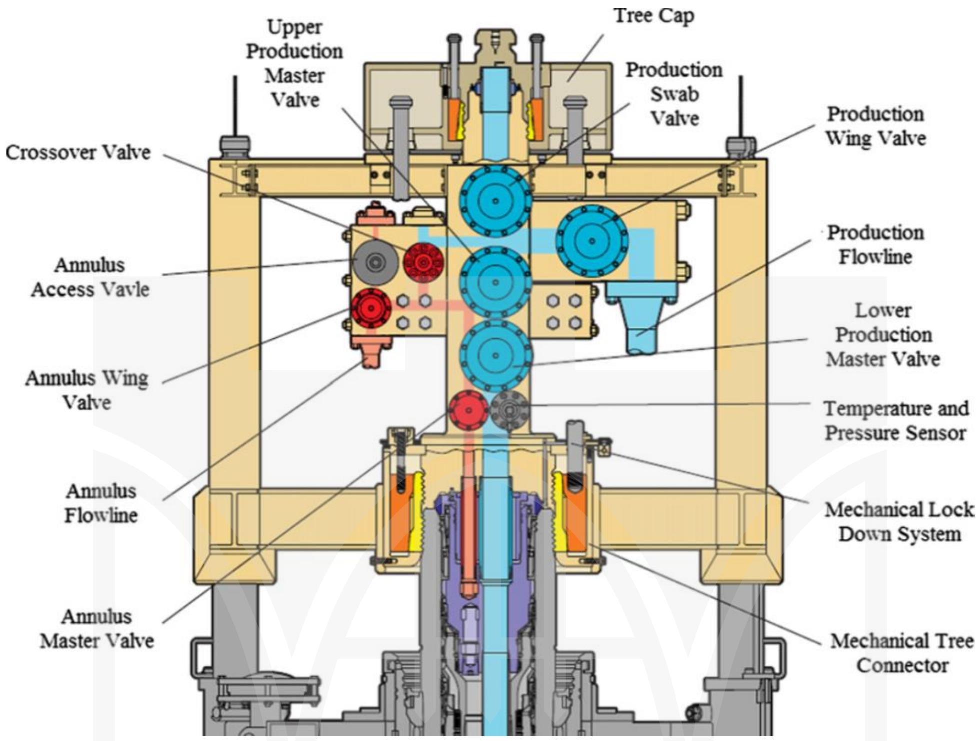

Fig. 2. Valves in Christmas Tree [Dril-Quip]

The valves in the Christmas Tree are controlled via a subsea control module mounted directly on the XT. The subsea control module contains the electronics, hydraulics and instrumentation needed for the safe and effective control of valves in the XT and the Downhole Safety Valve. In addition, the subsea control module is responsible for the distribution of the electric current monitoring signal and for communication with the surface. Modern subsea control modules must have reliability for water depths of up to 3000 meters and pressures of 20,000 psi (138 MPa).

In order to allow for the closing or opening of valves directly and independently of the control system, Christmas Trees are equipped with a panel, which allows for the direct control valve to use the remotely operated vehicle (ROV). Direct control of valves may be necessary for the assembly or disassembly of the XT of maintenance or failure of the control system.

3. Downhole safety valve

A very important valve, which is not located in the Christmas Tree, but it is controlled by it, is the Downhole Safety Valve (DHSV). The DHSV is mounted in a completed wellbore at a depth ranging from 100 to 500 meters below seabed. It is a flap-type valve and it is intended to prevent the uncontrolled release of hydrocarbons from the lode in the event of an emergency when other valves have failed. The DHSV is controlled with hydraulic fluid by the Christmas Tree.

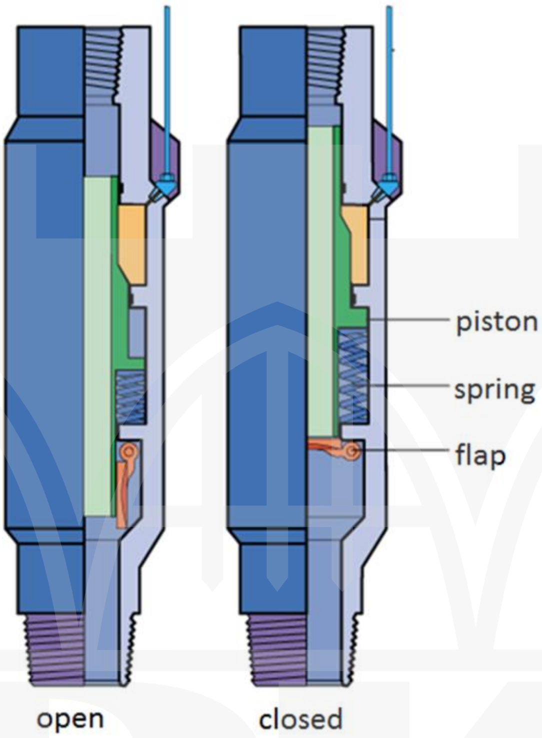

Fig. 3. DHSV valve [www.whcp-oilgas.com]

4. Failure Mode and Effects Analysis

Failure Mode and Effects Analysis (*FMEA*) is a qualitative method, which is used to identify potential errors or defects, and to assess their effects. Many industries require for the FMEA to be used in the design of technical systems and that its sheets to be part of the system documentation. Provisions in the oil industry also require a similar analysis. The analysis uses specific FMEA sheets, in which, inter alia, it distinguishes the failure modes of individual elements or severity of the ranking. Failure mode is a description of a possible malfunction of the element that prevents the required function, which answers the question; how the machine crashes. Modes and causes of damage for the valves depend on the particular design. For a standard subsea gate valve installed in the Christmas Tree, the following typical modes and their corresponding causes as well as mechanisms of damage may be mentioned:

Table 1.

Failure modes and possible causes of it

Failure mode	Possible causes
Fail to close	• Fault control system, • Too high hydraulic pressure in the supply line rod chamber, • Locked return hydraulic line, • Spring failure, • Internal leak.
Fail to open	• Fault control system, • Too low pressure in the hydraulic circuit valve supply, • Damaged piston valve, • Spring failure, • Internal or external leak, • Locked hydraulic return line.
Premature or uncontrolled shutdown	• Fault control system, • External leak.
Internal leak	• Seal failure.
External leak	• Seal failure, • Unsealing the valve body.

4.1. Classification of the severity of fault

The classification of the severity of the effects provides the qualitative dimension of the worst potential consequences of design errors or equipment failures. Each identified failure mode and analysed element is subject to the classification of the severity of the impact. Classification is used in both FMEA and FMECA. The categories are divided into:

- Category I (catastrophic) – failure results in death of workers or huge loss of devices preventing further execution of the planned objectives of the system.
- Category II (critical) – failure causes the degradation of the system beyond acceptable limits, creating a security risk (contributing to the death or injury of employees, if they are no taken steps to combat the risk).
- Category III (severe) – the failure of the system degrades the bounds of safety, but there is a possibility to appropriately counteract the effects.
- Category IV (reduced) – failure does not degrade the whole system performed beyond the acceptable limits of safety, causing one of the various disadvantages of the system.

- Table 2

- **FMEA sheet for PMV**

Description of item: Production Master Valve			Description of failure			Effects of failure		Severity	Recommended action to reduce the risk	Commentary
Nr	**Function**	**Operating mode**	**Failure mode**	**Potential cause of failur**	**Detection**	**On subsystem**	**On whole system**			
1	It allows on the flow of hydrocarbons from the wellhead; provides isolation between wellhead and production tubing	Valve in open position	Fail to close	Fault control system	D	Is not possible to close valve on demand; continuous flow of hydrocarbons through the valve	The closure of Christmas Tree by the valve is impossible. Other valves on the production line are needed to work	Category II: Critical	Regular inspections and testing of the control system	
				Too high hydraulic pressure in the supply line rod chamber	D				Regular inspections and testing of the hydraulic system	
				Locked hydraulic return line	U				Regular inspections and testing of the hydraulic system	
				Spring failure	U				Proper maintenance	

5. Results

Analysed PMV, PWV, AMV and DHSV. Distinguished two modes of operation: the valve in the open and closed positions and whether the damage is detectable, and each failure mode has been classified according to the classification of the severity of the impact. Table 2 presents an exemplary FMEA sheet that was used while analysing.

The Downhole Safety Valve is the primary barrier and is designed to cut off the Christmas Tree from lodes. For DHSV in the open position, the most dangerous failure mode is "left open the valve," which have been classified in the classification of the severity of fault "leakage through the valve" as a critical fault. Failure mode "fail to close" is extremely dangerous when the situation requires, for example, a fire on the platform. In this case, it is necessary to ensure the proper functioning of the valves in the Christmas Tree. If the secondary barrier does not fulfil its function, the platform will still be transmitting hydrocarbons, which will result in such a situation as an explosion on the surface. Failure mode "leakage through the valve" causing damage to the sealing flap is dangerous due to the fact that the valve does not close the flow of hydrocarbons in the situation required. It is then necessary to activate the valves in the XT, which violates the integrity of the subsea safety at oil and gas production. A major failure mode is uncontrolled shutdown. In this case, there is no assurance that the valve will work and close properly, and on the other hand, there is the possibility that the valve closes spontaneously in normal production, causing downtime and thus financial losses.

The secondary barrier is the Christmas Tree and its main valve is the Production Master Valve. In case of failure, DHSV is the first valve that is designed to cut off the flow of hydrocarbons through the Christmas Tree. This is a very important component of the XT because its failure contributes to an increased risks associated with not closing the whole XT. Failure modes in the basic gate valves of XT are classified from serious to catastrophic consequences. All considered, gate valves (PMV, PWV, AMV) in both operating modes external leak hydrocarbons cause disastrous consequences. In such a situation, it requires keen DHSV or the XT, otherwise it may lead to an ecological catastrophe caused by the contamination of seawater, and thus huge financial losses. If the DHSV works, an ecological catastrophe does not occur, but it is necessary to draw all the XT and replacement of the damaged valve. If the DHSV does not work, but the other valve is closed, it will not be possible to immediately draw the XT. In such a situation, injection of heavy drilling fluid into the wellbore would be needed. Each day of downtime in production is associated with financial losses, but also to draw all the XT generates additional costs. With the exception of an external leak, all failure modes in AMV have serious consequences. Analysing PMV and PWV in operation in the open position failure mode "fail to close" "internal leak" caused damage to the piston seal and the "uncontrolled shutdown" necessitate the activation of other valves, and thus in case of requiring situation increases the probability associated with the failure to close the entire XT. In addition, the occurrence of even one of these failure modes leads to stoppage of the whole production in order to repair the fault. In contrast, the occurrence of leakage caused by damage to the inner piston seal also will stop production because the hydraulic pressure in the chamber, the rod falls, and thus the valve closes. Failure mode "uncontrolled shutdown" is not a dangerous fault because it does not contribute to an increase in the danger of the production of hydrocarbons, but the effects of this mode are felt from the economic side.

The analysis can be concluded that for each basic gate valve of XT, the most dangerous are an external leak and the failure mode "fail to close" in the open position of the valves. Any failure of an individual valve that makes the extraction of hydrocarbons becomes less and less secure. An indispensable component of the safety system of subsea production is the DHSV, the most dangerous defects can occur in the open position of the valve. The DHSV and the Christmas Tree complement each other, thus ensuring the security of oil and gas production.

References

[1] Norsok Standard D-010.

[2] Perrin D., *Well Completion and Servicing*, Technip 1999, 153-156.

[3] Rausand M., *Reliability of Safety-Critical Systems: Theory and Applications*, Wiley 2014, 53-76.

[4] Samir D., *Fundamentals of Oil & Gas Industry for Beginners*, Notion Press Chennai 2015.

[5] Young B., Qiang B., *Subsea Engineering Handbook*, Elsevier, 2010.