Proceedings of the Twenty-fifth (2015) International Ocean and Polar Engineering Conference
Kona, Big Island, Hawaii, USA, June 21-26, 2015

ISBN 978-1-880653-89-0; ISSN 1098-6189
www.isope.org

Risk analysis of annular preventer performance in multiplexed submarines BOP based on ISO 31.000 and API 581 standards

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ABSTRACT

After the Macondo accident in the US, which is estimated loss of US$ 42 billion, risk analysis of the BOP (Blowout Preventer) has gained great importance in the projects of exploration and development of oil fields. This work has deepened the analysis of the risk of triggering preventer annular (one of the functions of the BOP), mapping the sensitivity of maintenance, redundancy design and service life of the components, according to the guidelines of the standards API 581 (risk-based inspection) and ISO 31000 (risk management). The reliability model was built based on the fault tree and it was assumed a constant failure rate of systems and components over time. It is used as a reference a BOP with two annular preventers. The simulations showed that increasing frequency of preventive maintenance, in addition to improving the quality of management of maintenance and lifespan of some components can significantly reduce the risk of annular BOP failure. On the other hand, the gain in reliability by adding redundancy is insignificant when compared to the loss of reliability caused by the loss of redundancy of the system.

KEY WORDS: annular BOP, API 581, ISO 31.000, reliability.

INTRODUCTION

The BOP (blowout preventer) is a valve consisting of multiple preventers, installed on the head of an oil well, designed to isolate the well from the surface. There are two classes of preventers in the BOP: rams and annulars. They are multiple in order to make the system redundant and are used according to the element (pipe) inside the BOP. An annular preventer is one of these preventers present on the BOP that can close and seal an opened well or against a wide range of pipes. The model of electro-hydraulic drive of an annular BOP was built based on patents and technical standards API SPEC 16D ((API), American Petroleum Institute, 2004) and API STD 53 ((API), American Petroleum Institute, 2012) that governs its operation (Fig. 1).

A brief description of system operation follows. Initially, the system stays with the opening side of the annular chamber pressurized, while the closing chamber is maintained without pressure, to maintain the annular BOP opened. In the event of a "kick" (influx from formation into the well), the annular BOP is closed, draining the pressure of opening chamber and pressurizing the closing side chamber to close the annular BOP and prevent the influx to reach the surface.

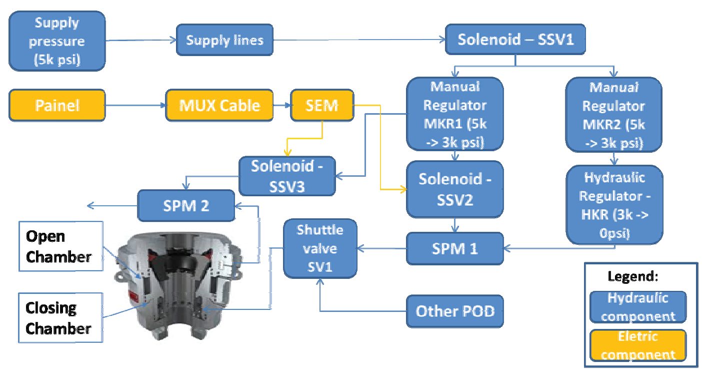

Figure 1: Schematic of electro-hydraulic drive of annular BOP

The electro-hydraulic control mechanism for opening and closing the annular BOP is basically consisted by a pressure supply, a power line, POD (Point Of Distribution, consisting of SEMs and manifold), MUX cable, chambers of the annular BOP and its respective insert ("rubber"). The POD manifold is constituted by a set of pressure regulating valves, solenoids and SPMs.

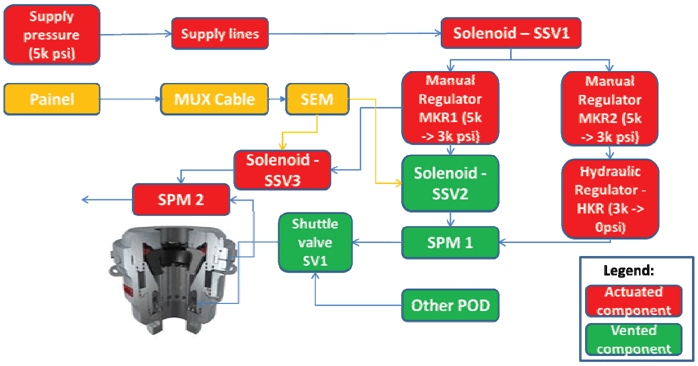

Figure 2: State diagram of the system components in the situation annular BOP opened

To pressurize a chamber of annular BOP, an electrical signal, which is provided by a command in the panel, is transmitted by the MUX cable (multiplexed siganl) to the POD. The signal is then received by the SEM (subsea electrical module) located in the POD and is responsible for energizing the solenoid (located on the Pilot line) which, in turn, directs the pilot pressure to the SPM (Subsea Plated Mounted valve) making it open. When the SPM is opened, it transmits hydraulic pressure to the corresponding chamber of the annular BOP. The chamber acts as a piston pressing the insert ("rubber") to compress and seal a drilling pipe and isolating the well. Figures 2 and 3 illustrates the working mechanism of system components in changing state of open well (Fig. 2) to closed well (Fig. 3).

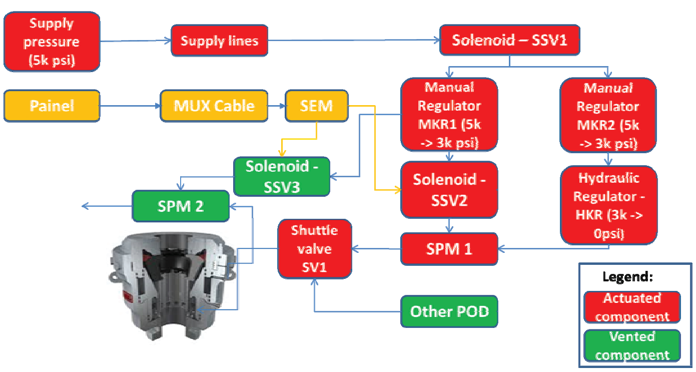

Figure 3: State diagram of the system components in the closed annular BOP situation

Table 1: Comparison of the annular BOP components states for open and closed cases

No	Function	Initial State		Final State	
		Open chamber	Closing chamber	Open chamber	Closing chamber
CL (Conduit Line)	Transmit hidraulic energy stored at surface to BOP	Pressurized	Pressurized	Pressurized	Pressurized
SSV1 (Solenoid valve 1)	Allows hydraulic energy to selected POD	Actuated	Actuated	Actuated	Actuated
MKR1 (Manual Koomey Regulator valve 1)	Manual regulator valve of mail function line. Input: 5.000psi. Output 3.000psi	Actuated	Actuated	Actuated	Actuated
MKR2(Manual Koomey Regulator valve 2)	Manual regulator valve of pilot function line. Input: 5.000psi. Output 3.000psi	Actuated	Actuated	Actuated	Actuated
HKR2 (Hidraulic Koomey regulator valve 2)	Main function line hydraulic remote regulator valve. Input: 3.000psi. Output: desired	Actuated	Actuated	Actuated	Actuated
SSV2 (Solenoid valve 2)	N/C Solenoid that actuates SPM1	De-energized (closed)	Actuated	Actuated	De-energized (closed)
SPM 1 (Subsea Plated Mounted valve 1)	N/C Valve that comunicates the main function line to close chamber	De-energized (closed)	Actuated	Actuated	De-energized (closed)
SSV3 (Solenoid Valve 3)	N/C Solenoid that actuates SPM2	Actuated	De-energized (closed)	De-energized (closed)	Actuated
SPM 2 (Subsea Plated Mounted valve 2)	N/C Valve that comunicates the main function line to open chamber	Actuated	De-energized (closed)	De-energized (closed)	Actuated
SV (Shuttle Valve)	Valve that transmit pressure from one or other POD to annular BOP chamber.	Actuated	Vented	Vented	Actuated
Opening Chamber	Chamber of the piston side that will open annular BOP	Actuated	Vented	Vented	Actuated
Closing Chamber	Chamber of the piston side that will close annular BOP	Vented	Actuated	Actuated	Vented
Insert	Seal (rubber) that will seal the well	De-energized (opened)	De-energized (opened)	Energized (close)	Energized (close)
SEM (Subsea Electric Module)	Module that will convert signal sent from painel to a comand at a solenoid valve	Energized	Energized	Energized	Energized
MUX Cable	Cable that will transmit the signal sent from the painel at surface to BOP.	Energized	Energized	Energized	Energized

Modeling the problem

Based on the system operation mechanism described above, the components of this model were analyzed according to the methodology of ISO 31000 standard. According to this standard, it is fundamental to construct an FMEA (Failure Mode and Effect Analysis), identifying the failure mode of each component, its causes, the fault effect on the system, the MTTF (Mean Time To Failure, according to OREDA and BSEE *apud* PER HOLAND, 2012) and measures taken in case of failure, as shown in Table 2.

Table 2: FMEA of annular BOP components

No	Failure	Cause	Efect over		Failure probability		Detection	Protection
			Other component	System	MTTF (hours of BOP)	Source		
CL	Leaking	Erosion Corrosion Vibration	Loss of PODs hidraulic pressure	Annular BOP do not close correctly	2439024	OREDA 2009	Pumps on frequently Low pressure at PODs	Swap to other supply line
SSV1	Stuck in open position	Solenoid not energized Leaking	Loss of PODs hidraulic pressure	Annular BOP do not close	66358	OREDA 2009	No indication of flux when actuating a function Pumps on frequently	Swap to other POD
MKR1	Wrong output pressure	Spring broken Leaking Inadequate ajustment	Wrong output hidraulic pressure in PODs pilot side	Annular BOP do not close correctly	117997	BSEE 2013	Wrong pressure at PODs	Swap to other POD Swap to other annular BOP
MKR2	Wrong output pressure	Spring broken Leaking Inadequate ajustment	Wrong output hidraulic pressure in PODs main function side	Annular BOP do not close correctly	117997	BSEE 2013	Wrong pressure at PODs	Swap to other POD Swap to other annular BOP
HKR2	Wrong output pressure	Spring broken Leaking Inadequate ajustment	Wrong output hidraulic pressure in PODs main function side	Annular BOP do not close correctly	117997	BSEE 2013	Wrong pressure at PODs	Swap to other POD
SSV2	Stuck in open position	Spring broken Leaking Solenoid not energized	SPM not actuated	Annular BOP do not close	66358	OREDA 2009	No indication of flux when actuating a function Pumps on frequently	Swap to other POD Swap to other annular BOP
SPM	Stuck in close position	Spring broken Leaking Pilot pressure not received	Annular BOP do not close	Annular BOP do not close	1011404	BSEE 2013	ROV indication No indication of flux when actuating a function	Swap to other POD Swap to other annular BOP
SV	Leaking	Leaking	Annular BOP do not close	Annular BOP do not close	2515694	BSEE 2013	ROV indication Annular BOP will not seal pressure More gallons than expected to actuate function	Swap to other POD Swap to other annular BOP
Chamber	Leaking	Leaking	Annular BOP do not close correctly	Annular BOP do not close correctly	185185	Nilo Jorge	More gallons than expected to actuate function	Swap to other annular BOP
Vent	Vent side stucked	Hidraulic counter pressure	Annular BOP do not close correctly	Annular BOP do not close correctly	62500	BSEE 2013	Less gallons than expected to actuate function	Swap to other annular BOP
Sealing	Internal leaking	Aging	Annular BOP do not close correctly	Annular BOP do not close correctly	61416	BSEE 2013	Annular BOP will not seal pressure	Swap to other annular BOP
SEM	Failure in command SPM	Electrical failure	POD will not anwer	Annular BOP do not close	43827	BSEE 2013	Annular BOP will not seal pressure	Swap to other POD
MUX	Failure to transmit signal	Electrical failure	POD will not anwer	Annular BOP do not close	63938	OREDA 2009	Annular BOP will not seal pressure	Swap to other POD

Next, the fault trees analysis (FTA) of the annular BOP and its subsystems were built using the top-down approach, based on FMEA results. BOPs that have more than one annular preventer actuate only one each time, even though they are redundant. The starting point is the assumption that at least one is required to close the annular well (i.e., drive failure occurs when all annular fail), as shown in Figures 4, 5 and 6.

1 - To fail all annular BOP system:

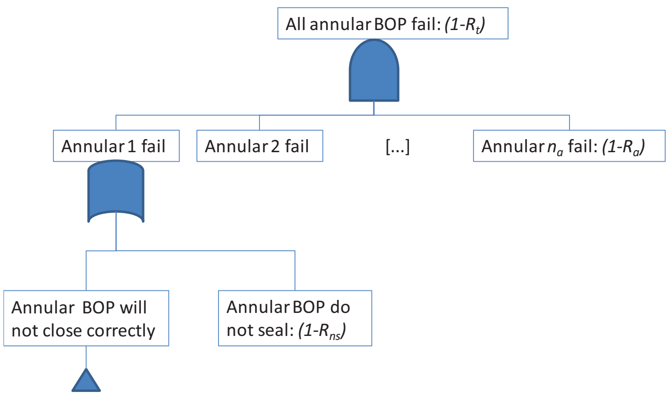

Figure 4: FTA for annular BOP complete failure

2 – Failure of one single annular BOP:

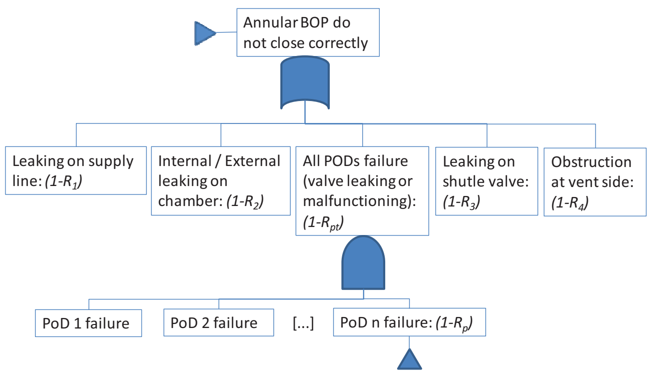

Figure 5: FTA for a single annular BOP failure

3 – Failure of a single POD:

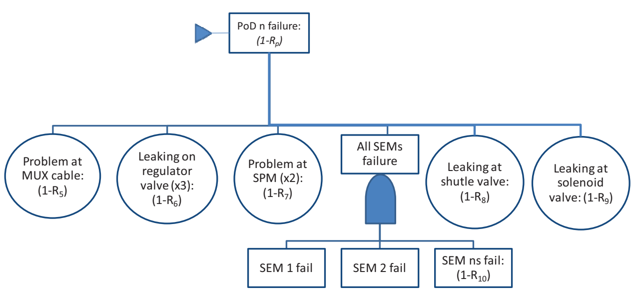

Figure 6: FTA POD

Based on the fault trees analysis, the annular BOP probability of failure (and its liability) can be estimated.

By definition of liability (R), the relation with the non-liability (F) is given by:

$$F = 1 - R \tag{1}$$

For system with serial port (equivalent to logical OR), liability of the system is the product of its individual component liabilities:

$$R = \prod_{i=1}^{n} r_i \tag{2}$$

For systems with parallel port (equivalent to logical AND), non-liability of the system is the product of its individual component liabilities:

$$F = \prod_{i=1}^{n} f_i \tag{3}$$

Due the lack of large amount of failure date, it was assumed the hypothesis that failure rate of systems and components are constant along time (t):

$$R(t) = e^{-\frac{t}{TMEF}} \tag{4}$$

We arrive at the following equations describing the reliability of the model:

Failure of all annulars BOP:

$$R_t = 1 - (1 - R_a)^{na} \tag{5}$$

Failure of a single annular BOP:

$$R_a = \left(R_1.R_2.R_{pt}.R_3^{ns}.R_4^{np-1}\right).R_{ns} \tag{6}$$

Failure of all PODs:

$$R_{pt} = 1 - \left(1 - R_p\right)^{np} \tag{7}$$

Failure of a single POD:

$$R_p = R_5.R_6^3.R_7^2.R_8^{(np-1)}.R_9^3.\left(1 - (1 - R_{10})^{n_{sem}}\right) \tag{8}$$

RESULTS AND ANALYSIS

As reference to compare the evolution of risk, it was used a BOP with the following parameters:

- 3 lines of supply (2 Conduit lines and 1 Hot Line);
- 2 PODs, each pod has two SEMs;
- 2 annular BOPs;
- Preventive maintenance every 720 days;
- Mid management maintenance (50%);

Introducing the values of MTTF of the components compiled by (Per Holand, 2012) on the equations obtained, the MTTF of the modeled system was reached. The results of reliability of an single annular BOP and a single POD as a function of time are shown in Figure 7. Additionally, the results for the reliability model are compared with the reliability of the system considering the MTTF of the annular BOP system as a whole. Moreover, the reliability of the annular BOP is also compared with the model of Petri nets obtained by (Liu Zengkai, 2013).

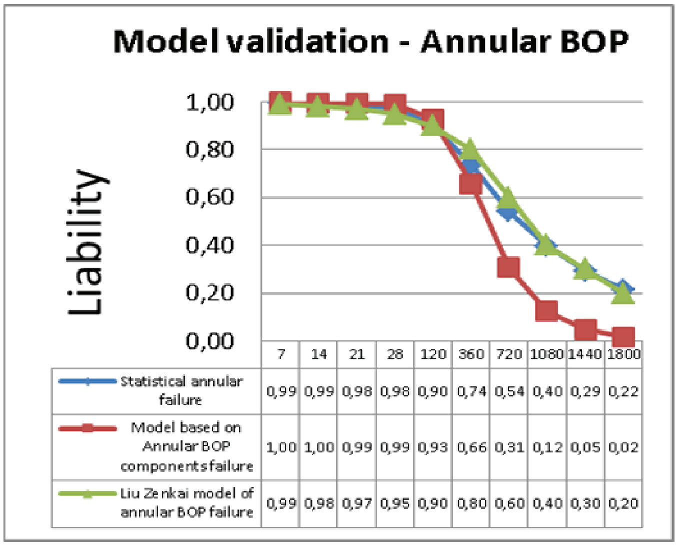

Figure 7: Comparison of the reliability x time (days) of the annular BOP of individual components, and System Petri net fault

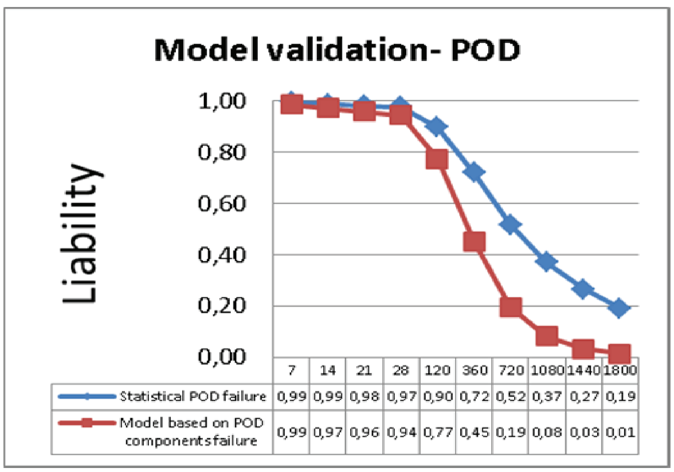

Figure 8: Comparison of the reliability x time (days) of the annular BOP calculated by models of individual components and system failure

The MTTF value of the component model was validated by comparison with statistics of system failure, considering the uncertainty of the estimate based on the Chi-square distribution.

$$TMEF_{calc} = \frac{s}{n} \tag{9}$$

Where s is the total time that the system (or component) is in operation and n is the number of failures recorded. The upper and lower limits of the confidence MTTF obtained statistically are determined with 95% confidence according to (PER HOLAND, 2012).

$$TMEF_{\sup} = \left(\frac{1}{2s} \chi^2_{0.95,2n} \right)^{-1} \tag{10}$$

$$TMEF_{\inf} = \max\left[0; \left(\frac{1}{2s} \chi^2_{0.05,2(n+1)} \right)^{-1} \right] \tag{11}$$

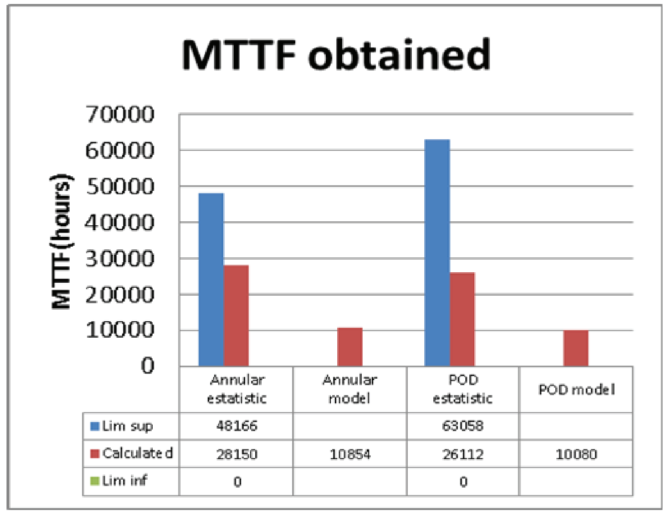

Figure 9: Comparison of the calculated MTTF for the annular BOP and for the POD with the value obtained statistically considering the uncertainty.

It was observed a good grip of the model relative to that achieved statistically, in accordance to Figure 9.

With the model validated, then, the influence of the reduction in the frequency of preventive maintenance (1) have been simulated, in addition to improving the quality of maintenance (2) and the service life of system components (MTTF) (3) and the redundancies of the system (4) were studied and how they affect the risk of triggering the annular BOP. The risk of failure refers to the probability that none of the annular BOP will plug the well when triggered. The variation in risk (namely relative risk) was calculated indirectly by following the methodology of API 581 ((API), American Petroleum Institute, 2008) and comparing the risk obtained with the predicted risk for the failure of the reference BOP. This strategy was adopted because of the difficulty in calculating the damage factor (system of great complexity) and the cost factor (due to the peculiarity of estimating the cost of cleaning a blowout to each well (Etkin, 1999)).

$$Risk_{API581} = \left(g_{ff} . F_{ms} . D_{ft} \right) FC \tag{12}$$

$$g_{ff} = \frac{1}{TMEF} \tag{13}$$

$$R(t) = e^{-g_{ff}.t} \tag{14}$$

$$g_{ff} = \frac{-\ln(R)}{t} \tag{15}$$

where,

gff is the rate of failure / BOP day;
Fms is the factor of system maintenance (management factor);
Dft is the damage factor;
FC is the cost of a failure (blowout);

$$Risk_{relative}(\%) = \left(\frac{Risk_{cond.estudied}}{Risk_{reference}} - 1 \right).100$$

$$= \left(\frac{-\ln(R_1).t_0.F_{ms1}.D_{ft1}}{-\ln(R_0).t_1.F_{ms0}.D_{ft0}} - 1 \right).100 \qquad (16)$$

$$D_{ft1} \approx D_{ft0} \qquad (17)$$

$$Risk_{relative}(\%) = \left(\frac{\ln(R_1).t_0.F_{ms1}}{\ln(R_0).t_1.F_{ms0}} - 1 \right).100 \qquad (18)$$

1 - Change in the number of redundancies

Initially it was varied, one by one, the number of redundancies of the system to find out the influence on the increment of failure risk. The impact of supply lines (conduit lines and hot lines), number of PODs and numbers of annular BOP and SEMs / POD were studied, as shown in Figure 10:

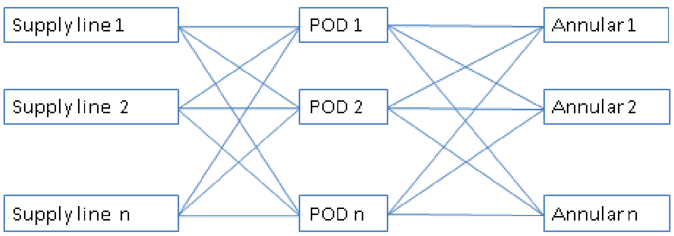

Figure 10: Representation of the redundant drive system of the annular BOP

The results of the simulations can be seen below:

1.1 Varying the number of pressure supply lines

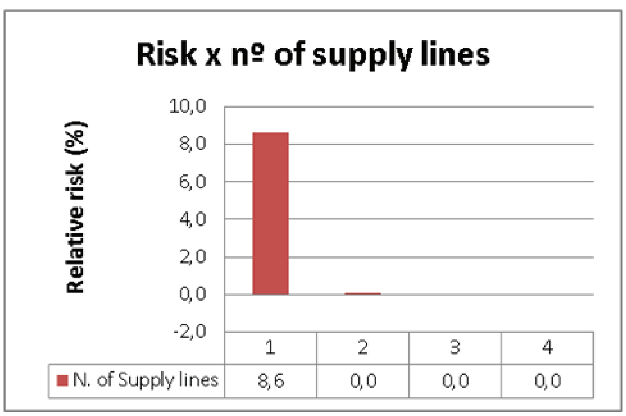

Figure 11: Graph of relative risk x number of supply lines

1.2 Variation in the number of PODs

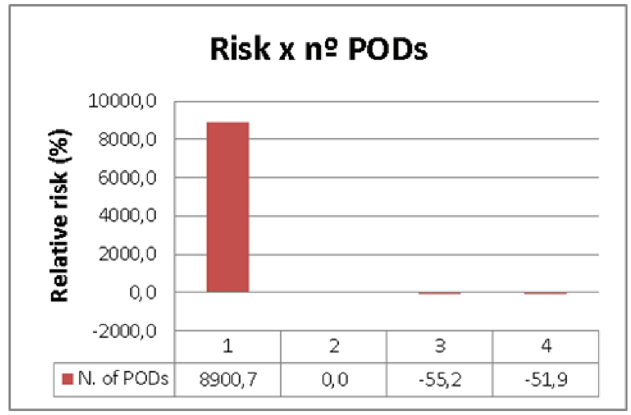

Figure 12: Graph of relative risk x number of PODs

1.3 Varying the number of annular BOP

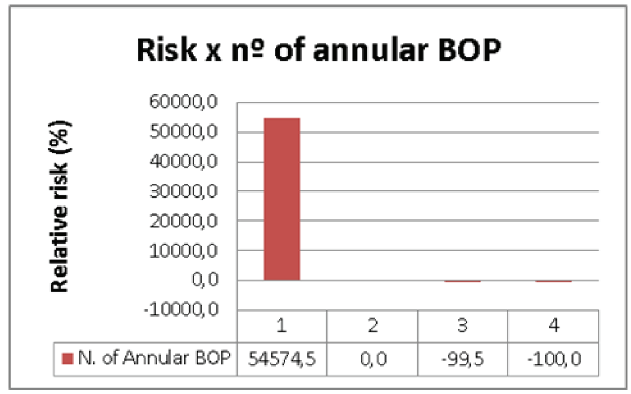

Figure 13: Graph of relative risk x number of annular BOP

1.4 Variation in the number of SEMs / POD:

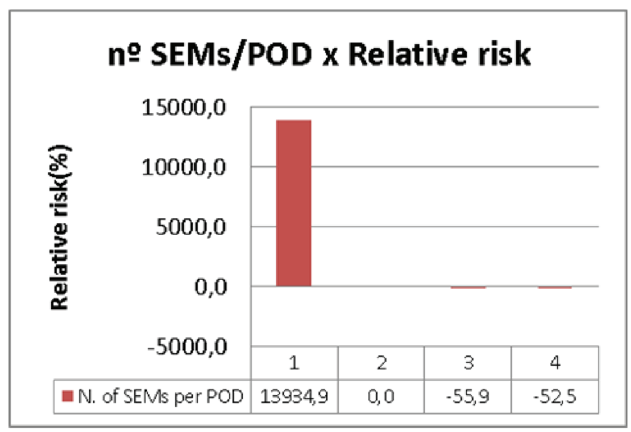

Figure 14: Graph of relative risk x number of SEMs/POD

2 Varying the frequency of maintenance

According to API 581 ((API), American Petroleum Institute, 2008) standard, the reduction of the maintenance interval tends to reduce the risk of system failure. The influence of time was studied at intervals of preventive maintenance (replacement and reconstruction of system components).

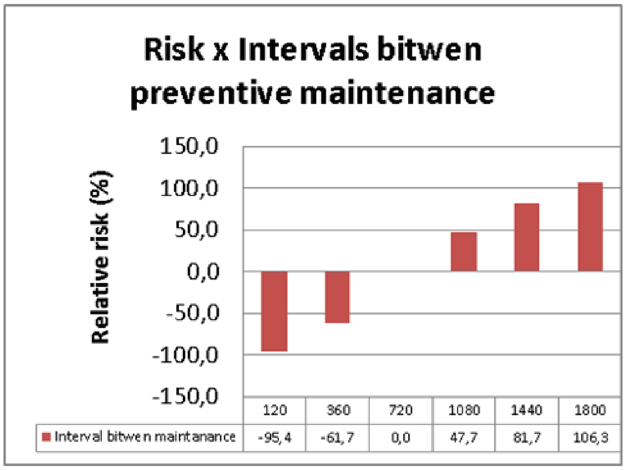

Figure 15: Graph of relative risk x interval between preventive maintenance (days)

3 Variation in the competence of maintenance:

According to API 581, the quality of maintenance can be measured by a score defined in Annex II of the same standard (obtained according to pre-established criteria). The management maintenance factor is calculated by:

$$F_{ms} = 10^{(-0,02*SCORE+1)} \quad (12)$$

And the variation in risk was calculated with the change in the score, as shown in Figure 16.

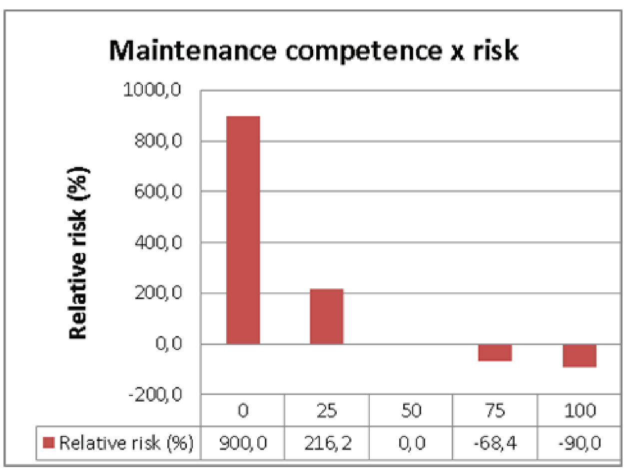

Figure 16: Graph of relative risk x score for management in maintenance

4 Variation of the MTTF of the system components:

One possibility found to reduce the risk of failing to trigger the annular BOP was to improve the reliability of its components (measured indirectly by its MTTF). The result of the study of variation of the risk of system failure due to the variation of the MTTF can be seen in Figure 17.

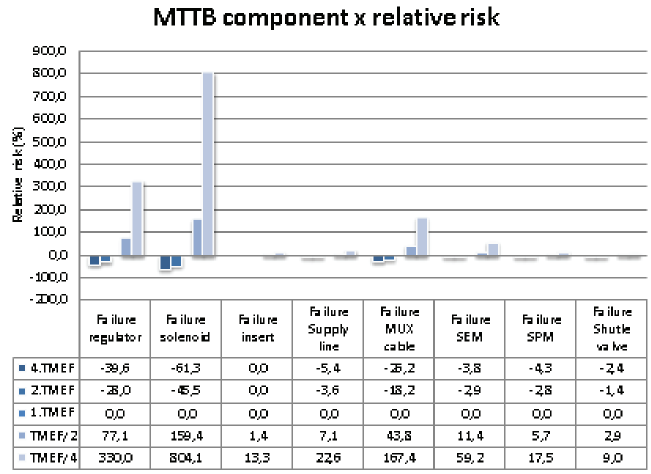

Figure 17: Analysis of variance of the MTTF of the components and their influence on relative risk.

CONCLUSIONS

According to the results of simulations, the loss of redundancies (of reference BOP) is much more severe for the risk of the annular BOP failure than by the decrease in risk provided by the gain of redundancies, as can be seen in Figure 18 and Figure 19:

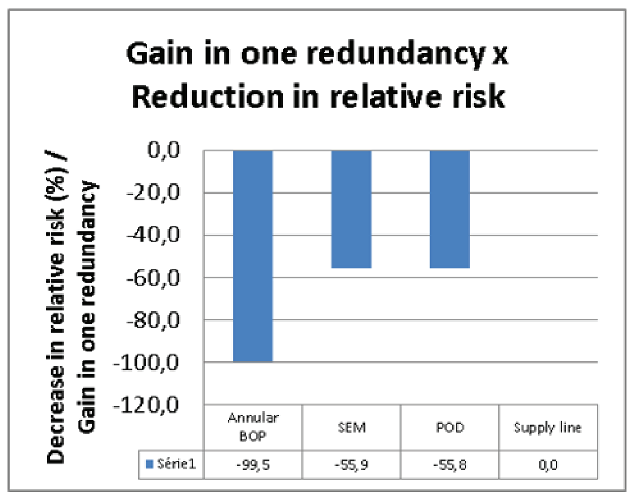

Figure 18: Reduce of relative risk x gain in redundancies

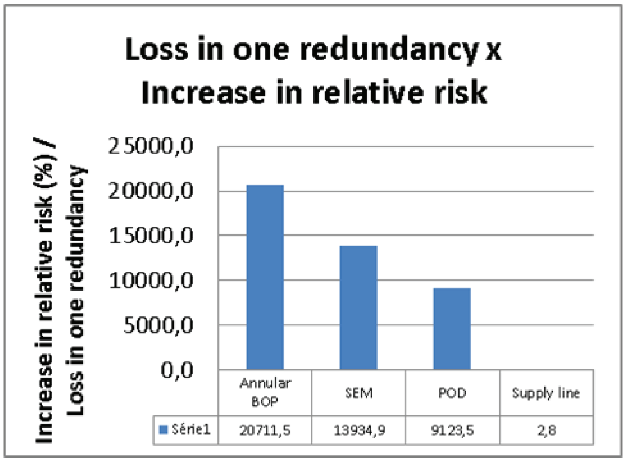

Figure 19: Increase of relative risk x loss in redundancies

The variation of the components MTTF produced much greater effects on the regulator and solenoid valves. This result can be explained by the amount of these elements connected in series to drive the annular BOP. It is noted that, in this model, improving the MTTF of components that have the lowest MTTF does not necessarily cause the greatest impact in reducing risk.

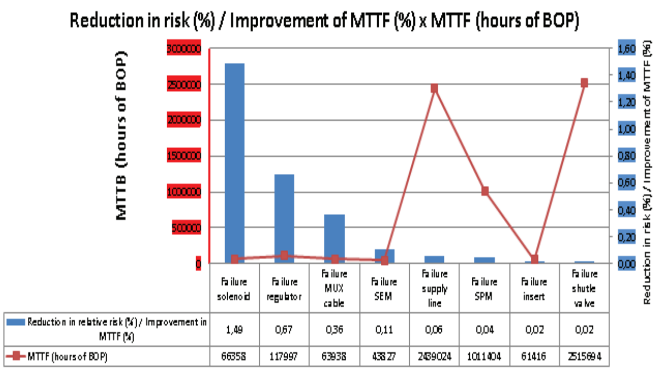

Figure 20: Comparison of relative risk / improvement of MTTF with the components of the annular BOP

Regarding the impact of preventive maintenance on the increased risk of system failure, it was observed that is easier to increase than to decrease the risk. According to results obtained, with good correlation, for the quality of maintenance management, the risk of failure in the drive decreases 1% for every 1% improvement in management. According to the same criterion, the risk of drive failure increases 8% for each 1% worsening in the management of maintenance (Fig. 21). Also, the relative risk increases by 0.13% for each day over the maintenance interval reference (or equivalently, the risk is reduced by 0.9% for each 1% it reduces the range of 720 days).

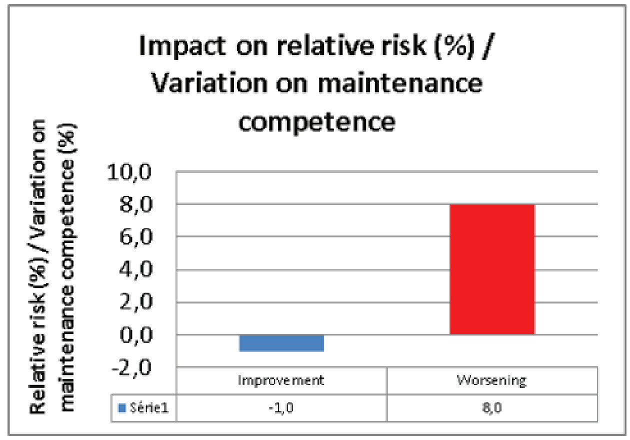

Figure 21: Influence of the quality of management of maintenance in the relative risk

Finally it is concluded that both the design improvement, the maintenance management can help reduce the risk of failure that drives the annular BOP.

ACKNOWLEDGEMENTS

I would like to thanks my colleagues from Petrobras, engineers Mr. Marcelo Monici, Mr. Fernando Fuentes Gonzales, Mr. Ruy Mittelztat and Mr. Gabriel Felipe da Silva for their contributions in reviewing this article. Special thanks for Mrs Ivete Maria Duarte in translating this article to English language.

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